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Impact of An Engineering Task on Development of Middle School Students' Engineering Design Practices (Fundamental)

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Abstract

The 2020 ASEE Framework for P-12 Engineering Learning outlines concepts, practices, and habits of mind to promote engineering literacy for graduating high school students. However, how these practices develop over time and what is appropriate for students to learn at different grade levels has not been determined. This study examined the development of middle school students' engineering practices through an informal, distance-learning engineering program. Ninety assessment videos from 30 students across three engineering design activities were analyzed using a qualitative research design. The study addressed three research questions: (1) How do students' reflections evolve over the course of the program? (2) Which engineering design practices do students reference in their videos? (3) How do features of the design challenge influence students' engagement with engineering design practices? Findings indicate that student assessment videos primarily focused on the performance of the physical model in meeting criteria, and despite explicit prompting, only 52% of students reflected on the design process, such as explaining design decisions. Additionally, two specific elements of the design challenge —open-ended design constraints and the complexity of the building process —seem to have promoted different types of engagement in the design process. This study contributes to the development of learning progressions for K-12 engineering education by providing a classification system for engineering design challenges. This system offers an empirically based framework for developing engineering activities tailored to various learning objectives, with implications for curriculum design and teacher professional development in K-12 engineering education.

Introduction

Engineering has gained significant traction as a crucial component of K-12 education in recent years [1] - [4]. However, without clear grade-band learning goals for engineering instruction, activities such as building bridges and roller coasters are often repeated across grades without explicit learning progressions [5]. To address this concern, the American Society for Engineering Education (ASEE) and Advancing Excellence in P12 Engineering Education (AE3) introduced a *Framework for P-12 Engineering Learning* (FPEL) [5]. This framework outlines concepts, practices, and habits of mind intended to foster engineering literacy among high school graduates. While providing a starting point, further research is needed to understand how these practices develop over time and what is appropriate for students at different grade levels. This study examines how middle school students engage with engineering practices to understand which FPEL engineering design practices are referenced by middle school students and how the type of engineering task influences engagement. The study was conducted in the context of an informal, distance-learning engineering program that required students to submit video responses to specific prompts following an engineering design challenge.

ASEE Framework for P-12 Engineering Learning

In 2018, the AE3 research collaborative brought together researchers, educators, industry professionals, and policymakers to create a guide for engineering learning in K-12 settings [5]. The authors of the FPEL raised concerns that current engineering learning lacks clear learning progressions, promotes misconceptions, and fails to adequately prepare students for engineering pathways. For example, a popular "engineering-like" design activity is to build a bridge out of spaghetti and test until failure [5, p. 11], and this same activity is often repeated across elementary, middle, high school, and even undergraduate courses to support the development of engineering design practices [6]. Without any scaffolding or intentional progression of learning goals, teachers are "falsely comforted by an expectation that their students are successfully identifying and learning the often difficult-to-understand, discipline-specific engineering concepts from these experiences in a manner that can be transferred to novel concepts" [5, p. 11].

The resulting framework emphasized a three-dimensional approach to engineering learning where students "orient their ways of thinking by developing *engineering habits of mind*, be able to competently enact *engineering practices*, and appreciate, acquire, and apply when appropriate, *engineering knowledge* to confront and solve the problems that they encounter" (p. 39). Both the habits of mind and engineering practices are seen as core to achieving engineering literacy for all students, while engineering knowledge encompasses a broad domain of concepts that can be drawn upon to support engineering learning. A performance matrix (Table 1) is provided within the framework to describe the desired knowledge at the end of high school, in support of intentional teaching strategies and assessments for engineering literacy.

Table 1. Three-Dimensional Approach for Engineering Literacy [5]

Dimension 1: Habits of Mind	Optimism, Persistence, Collaboration, Creativity, Conscientiousness, and Systems thinking
Dimension 2: Engineering Practices	**Engineering Design:** Problem Framing, Project Management, Ideation, Prototyping, Decision Making, Design Methods, Engineering Graphics, Design Communication **Material Processing:** Manufacturing, Management & Precision, Fabrication, Classification, Casting, Molding & Forming, Separating & Machining, Joining, Conditioning & Finishing, Safety **Quantitative Analysis:** Computational Thinking, Data Collection, Analysis & Communication, System Analytics, Modeling & Simulation **Professionalism:** Ethics, Workplace Behavior & Operations, Intellectual Property, Technological Impacts, Role of Society in Technological Development, Engineering-Related Careers
Dimension 3: Engineering Knowledge	**Engineering Science:** Statics, Mechanics of Materials, Dynamics, Thermodynamics, Fluid Mechanics, Heat Transfer, Mass Transfer & Separation, Chemical Reactions & Catalysis, Circuit Theory **Engineering Mathematics:** Engineering Algebra, Geometry & Trigonometry, Statics & Probability, Engineering Calculus **Engineering Technical Applications:** Mechanical Design, Structural Analysis, Transportation Infrastructure, Hydraulic Systems, Geotechnics, Environmental Considerations, Chemical Applications, Process Design, Electrical Power, Communication Technology, Electronics, and Computer Architecture

Promoting Engineering Design Practices

A literature review of middle school engineering education from 2012 to 2022 found that 75% of the literature focused on promoting engineering practices. Among these, 95% emphasized design practices such as problem framing, ideation, and prototyping [7]. These practices are commonly developed through the design, building, and testing of physical models with instruction structured around the engineering design process (EDP) [8]. For example, students design and build a soda can crusher [9] or prosthetic arm [10] through a sequence of steps, which generally involve problem framing, gathering information, planning or brainstorming, building, testing, and evaluation, re-designing, and communication [11] [12]. Some researchers advocate for an iterative approach [13] [14] such as the design wheel by Chiu et al. (2013), which moves students from criteria, developing knowledge, ideation, prototyping, evaluation, refining, and then back to criteria [15].

Regardless of the specific EDP model, limited research has explored how students acquire and refine engineering practices. For instance, in a parachute design activity, teachers introduced fundamental concepts such as gravity and air resistance, intending for students to apply these ideas during the design and testing phases of their models [16] – [17]. While these studies highlighted the importance of evidence-based decision-making in design, the extent of student success in this area and the teacher's role in providing necessary scaffolding remain unclear. Students often move straight to constructing their designs, frequently without a clear plan, and rely on iterative tinkering to achieve functionality. This tinkering approach diverges from the intended learning goals of the FPEL [5], and researchers have proposed instructional strategies, such as problem-scoping prompts [18], to support the intended practices. Further research is necessary to evaluate the effectiveness of these strategies, their developmental suitability, and how teachers can best implement them to support student learning.

Additionally, the EDP is presented as a one-size-fits-all approach to tackling any engineering design problem [19]. In reality, however, authentic engineering work is highly context-dependent, with the specific problem shaping the tools, practices, and knowledge that engineers use [4] [20]. Despite this, little research has been conducted on how the type of K-12 engineering task—whether designing an insulating cooler [20], a roller coaster [21], or a water filter [22]—fosters the development of particular design skills. In education settings, the selection of engineering problems is often guided by the connection of those problems to science content, such as creating a composting system to teach conservation of matter [19] or building a solar oven to explore heat transfer [23]. While the effectiveness of these activities in teaching science concepts is debated and understudied [24], there is a simultaneous need to focus on how such tasks can help students develop engineering design skills, particularly when learning engineering is the primary goal. To ensure that engineering education aligns with its intended objectives, more research is needed to examine how the selection of tasks and the use of scaffolding strategies shape students' abilities to engage in engineering design practices. Because little is known about developmental learning progressions for engineering outcomes, this study was designed to understand which FPEL engineering design practices are employed by middle school students and whether the nature of the engineering task itself facilitates or impedes the use of particular practices. Our long-term goal is to support the creation of developmentally appropriate learning outcomes and instructional activities across K-12 that result in robust, age-appropriate engineering learning.

Study Context

This study explores how middle school students engage with a subset of FPEL engineering design practices during an informal engineering program, Space Club, which promotes engineering literacy alongside social and emotional learning. Established in 2014 by Communities In Schools of San Antonio (CIS-SA), Space Club involves a unique partnership between a CIS-SA social service professional specializing in mental health, teachers who contribute classroom content and management, and engineering mentors who add technical depth. Activities include engineering challenges focused on a space theme, such as launching a rocket or designing a robotic arm. The year-long program culminates with a city-wide competition where students work in teams to design a habitat on the Moon or Mars, focusing on engineering design, architecture, and mental health solutions.

In March 2020, Space Club programming was halted due to the COVID-19 pandemic and reconfigured for the fall of 2020 in a format compatible with distance learning. The result was *Mission to Moon*, an all-virtual 8-unit series of engineering design challenges centered around a lunar expedition. Each challenge involved instructional videos, digital engineering journals, and design tasks, culminating in students uploading assessment videos. The program aimed to maintain engagement and learning continuity in a virtual setting, with a focus on engineering literacy, career awareness, and social and emotional skills. In September 2020, the *Mission to Moon* curriculum and a self-paced teacher training program were made available nationwide. From October through December 2020, 52 middle schools participated in the program. Thousands of student assessment videos were uploaded, of which researchers selected a subset for analysis. Human subjects approval was granted for this study. The following research questions guided this study:

1. How do students' reflections evolve over the course of the program?
2. Which engineering design practices do students reference in their reflections?
3. What features of the design challenge are associated with students' engagement with engineering design practices?

Conceptual Framework

This study was grounded in research on human learning. Students are active agents in constructing meaning through the lens of their prior knowledge and experience [24]. Students often construct knowledge in intuitive and idiosyncratic ways, resulting in an understanding at odds with what the teacher intended them to learn. Furthermore, students' abilities to handle abstractions develop as they mature and gain experience [26] [27], and desired outcomes should be appropriate for the students' abilities. Disciplines that have been part of the K-12 curriculum for a long time have developed learning progressions, assessment boundaries, and carefully sequenced content and experiences designed to address students' developmental readiness and common misconceptions [27]. Such differentiated and sequenced content is currently lacking in K-12 engineering education.

Methods

Selection of Participants

Due to variations in implementation and demographics, homogeneous purposive sampling was employed, focusing on a single school site to minimize potentially confounding variables across schools. The selected school site was a public, urban, low socioeconomic status (SES) school in New York City. With 132 7th-grade participants, this school had the largest group of students participating at a single site. A teacher implemented the *Mission to Moon* curriculum in an elective STEM course, and 118 students uploaded a video for each lesson. From these, researchers randomly selected 15 male and 15 female students to analyze changes across time.

Selection of Engineering Activities

The *Mission to Moon* curriculum was divided into eight weekly engineering design activities connected to an overarching space exploration theme. Students worked independently to review the instructional video, completed the design challenge, and uploaded a video for the teacher.

To identify changes over time and the impact of different engineering tasks, researchers coded assessment videos from the first week and the last two weeks for a total of 3 engineering challenges (Table 2). All lessons included the same prompts for the assessment video. The first question was about the product students designed and built: "Share your design! How does it work?" The second part asked about the engineering process: "What happened during building and testing?" Researchers assigned an identifier to each video, which included a randomly assigned number (1 through 30) for each student and a reference to the lesson: "RC" represented the Roller Coaster activity, "Hand" for the Robot Hand, and "Rover" for the Rover mission.

Table 2. Coded Assessment Videos

	Roller Coaster (RC)	**Robot Hand (Hand)**	**Rover**
Week	1	6	7
Design Prompt	Design and build a safe and fun roller coaster to mimic the effects of the "vomit comet" used in astronaut training.	Design and build a robotic arm to pick up a rock sample.	Design and build a rover to transport rock samples.
Building Materials How constrained were students in building materials?	**Unlimited** - Paper - Paper Plates - Scissors - Tape	**Limited** - Tape - 3 straws - 5 pieces of string - 2 sheets of paper	**Limited** - Tape - Coin cell battery - Vibrating motor - 2 bendy straws - 1 paper cup - 3 pieces of paper
Design Constraints How open-ended were the design constraints?	**Open-Ended** - Ball stays in motion - Ball lands in cup - At least 1 turn	**Limited** - Mimics a hand and attached to an arm - Picks up ball and places in cup	**Open-Ended** Move ball 1 foot
Amount of Instruction How much guidance did students receive?	**Medium** Students are provided tips on how to use the materials.	**High** The instructional video describes how to build the arm with minimal room for variability.	**Low** The video only shows how to attach the battery to the motor.
Time per Build How much time will students likely need for one iteration?	**High** The final model is likely to be large and consume a significant amount of building materials and time for each iteration.	**High** The step-by-step instructions for the hand are extensive and require at least 20 minutes of building time.	**Low** The model is small, requires few materials, and likely takes little time for one iteration.

Development of Coding Guide

The initial phase of coding involved a timeline analysis to examine how students allocated time during their assessment videos. The prompts in the provided handouts guided this analysis, encouraging students to address both the *product* and the *process* with the following questions:

- Product: "Share your design! How does it work?"
- Process: "What happened during building and testing?"

From these prompts, three distinct markers were used in the timeline analysis:

1. Process: The student reflects on the process of designing and building the model.
2. Product Description: The student describes the features and functions of the model.
3. Product Showcase: The student conducts a demonstration to test how well the model meets the design criteria.

This coding approach provided insights into the proportion of time students dedicated to discussing the process of designing and building their models, compared to describing the final product or showcasing its performance. By analyzing these differences, the timeline analysis offered valuable data on how students engaged with and articulated their development of engineering practices. This information is crucial for understanding the emphasis students place on engineering design processes versus the performance of the final model.

The second part of the coding was to identify the engineering components derived from the performance matrix in the FPEL and considering the constraints and goals of the *Mission to Moon* program. Unlike traditional classroom settings, students completed activities asynchronously at home without direct teacher or peer support. Students relied on the provided handouts to guide them through the engineering design process in a step-by-step format. This approach diverged from the FPEL, which emphasizes that engineering design is a "messy, iterative, and complicated practice that follows no set procedure" [5]. However, the approach used in the program is highly consistent with the structure of engineering lessons used in K-12 settings [7] [28]. Additionally, the researchers faced the challenge of not being able to observe students during the activity; the only available data was in the form of student assessment videos. As a result, the study focused on identifying a subset of engineering practices described in the videos rather than fully addressing the FPEL's three-dimensional framework, which includes engineering habits of mind, engineering practices, and engineering knowledge.

The FPEL categorizes engineering practices and behaviors associated with the engineering field, into four areas: engineering design, material processing, professionalization, and quantitative analysis [5]. This study focused on engineering design practices (EDPs), a central element of pre-college engineering education [4][29]. Of the nine core EDP competencies, this study focused on four—problem framing, ideation, prototyping, and decision-making—due to their alignment with the *Mission to Moon* program's goals and their feasibility within the data collection constraints. Initially, prototyping and decision-making were coded as separate categories, but significant overlap between the two led to their consolidation into a single category, "decision-making." Each category was then subdivided into elements reflecting the FPEL's performance expectations (Table 3).

Table 3. Coding Guide for Assessment of Engineering Practices in Student Assessment Videos

Element	Description	FPEL Performance Matrix
Category I: Problem Framing		
Design Criteria	Student shows an understanding that the product needs to meet specific design criteria to solve a problem.	EP-ED-1 Problem Framing: Identify Design Parameters
Context	Student describes the larger context of the problem being solved.	EP-ED-1 Problem Framing: Problem Statement Development
Category II: Ideation		
Engineering Graphics	Student refers to or shows an engineering sketch of a design idea.	EP-ED-4 Ideation: Conveying Ideas through Sketching
Multiple Solutions	Student describes brainstorming multiple ideas for solving the problem.	EP-ED-4 Ideation: Brainstorming Techniques
Category III: Decision-Making		
Science-Informed	Student describes applying scientific knowledge to inform a design decision.	EP-ED-6 Decision-Making: Application of STEM Principles
Testing-Informed	Student describes the process of testing the model to gather data to improve the design.	EP-ED-6 Decision-Making: Evidence / Data / Logic-Driven Decisions
Material Properties	Student describes selecting materials to meet design criteria. Answers the question, why did you choose a material for the model?	EP-ED-5 Prototyping: Material Selection
Material Processing	Student describes the process of manipulating materials to meet design criteria. Answers the question, how did you manipulate the materials to create the model?	EP-ED-5 Prototyping: Manufacturing Process

Once the coding guide was developed, a second researcher reviewed the guide and provided feedback on the assessment of EDPs (e.g., ordinal or categorical). Although the guide was not created solely from the data using grounded theory, it was informed by the student assessment videos and adjusted as necessary [30]. A third researcher independently analyzed five videos using the coding guide to ensure consistency. The team met to discuss discrepancies, refine definitions, and update the coding guide. Once finalized, the guide was used by two researchers to independently code ten videos. From the two sets of scores, Cohen's Kappa was used to calculate the inter-rater reliability of K=0.92 [31], indicating high agreement. The researchers then split the remaining videos, with the lead researcher coding 65 videos and the third researcher coding 15 videos. The final coding guide is found in the appendix.

Results

Focal Areas determined by Timeline Analysis

This study analyzed 90 assessment videos from 30 students across three engineering activities. The first stage of coding involved a timeline analysis to measure the duration of videos and how students distributed their time in the reflection. The maximum possible video length is three minutes, but the average duration of the student videos was 52 seconds. The average video length increased over the course of the program:

1. Week 1 - Roller Coaster: 27 seconds
2. Week 6 - Robot Hand: 51 seconds
3. Week 7 - Rover: 79 seconds

The shortest video was 7 seconds, and the longest was 158 seconds. Female students' videos averaged 55 seconds, slightly longer than male students' videos at 50 seconds. The content of the videos focused on at least one of three elements: the process employed to design and/or build the model, a description of the final product, and a demonstration “showcase” of the final product. Each element (process, description, showcase) was flagged on the timeline to determine how much time students spent on each element. A description and exemplars for each coding category are presented in Table 4.

Table 4. Timeline Coding Exemplars

Video Element	Exemplar
Process The student reflects on the process of designing and building the model.	*The Roller Coaster requires a turn, which is why I used the plate for this. The ramp helps the ball gain energy also known as potential energy.* (S4RC) *I used construction paper for my arm and wrapped around my wrist area so it would stay put. I also put a few extra straws on the inside and outside over here for extra support so my hand wouldn't drop down. So those were a few revisions I had to make.* (S11Hand)
Product: Description The student describes the features and function of the model.	*This is what it looks like. I made it using a cup, a motor, and a coin cell battery.* (S5Rover) *This is my robotic arm. My arm is made out of cardboard, floss, embroidery string, and tape. The robotic arm is separated into two parts. The hand and the arm.* (S10RH)
Product: Showcase The student conducts a test of the prototype to show that it can meet design model.	The student drops the ping pong ball at the top of the Roller Coaster product and films as it falls down the track. (S10RC) Student demonstrates the robotic arm picking up a ping pong ball. (S6RH) The student connects the motor to the battery on the Rover and shows the Rover moving 1 foot across the table between two rulers. (S9Rover)

Students prioritized different elements during their assessment video including varying amounts of time spent describing their solution, showcasing how it works to meet criteria, and reflection on the design process. The order in which they presented the content also varied. Figure 1 illustrates the most common timeline patterns observed. Note that these timelines are represented as percentages of the total video duration to allow for visual comparison, as video lengths varied widely. For example, 35% of videos started with a mix of discussion around the process and product description and ended with testing the final model.

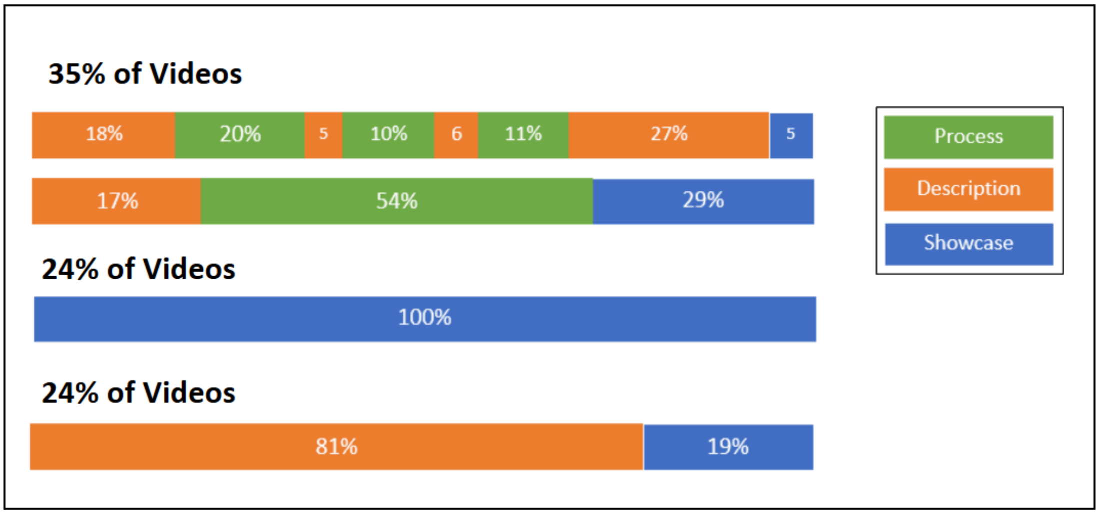

Fig. 1 Exemplars of the most common timelines

As shown in Figure 2, all 90 assessment videos included a showcase of the product, which involved conducting a test of the model meeting design criteria. However, only 64% of students described the features and functions of the model (product description), and only a little over half of the videos included reflection on the process of designing and building the model. Interestingly, 24% of the videos showcased the product without any student discourse about the product or process. These videos had minimal student dialogue, and the researchers did not find any elements of reflection on the process or description of the product. For example, a *Robot Hand* video in this category would show the student using the hand to pick up a ball and place it in a cup without any commentary.

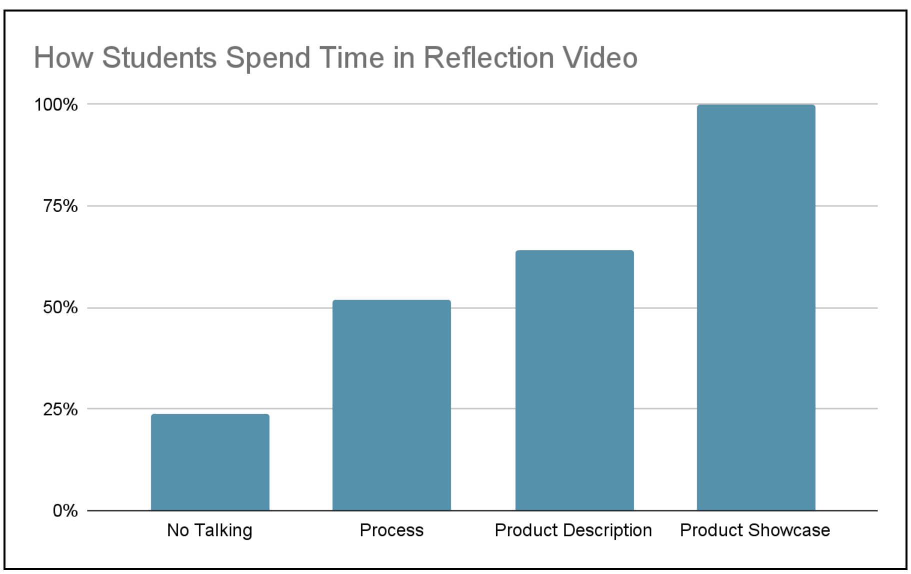

Fig. 2 Percentage of assessment videos that included each category of the timeline analysis

Sorting by engineering task, the 47 videos that included discussion on the process of developing the solution revealed an increase across the weeks (figure 3). In week 1 (Roller Coaster), only

40% of student videos included a description of their efforts to develop the design solution, followed by a slight increase to 47% in week 6 for the Robot Hand activity. After the final activity in week 7 (Rover), 70% of the students reflected on the design process during the video. These videos were further coded in the next phase to determine what aspects of design students discussed.

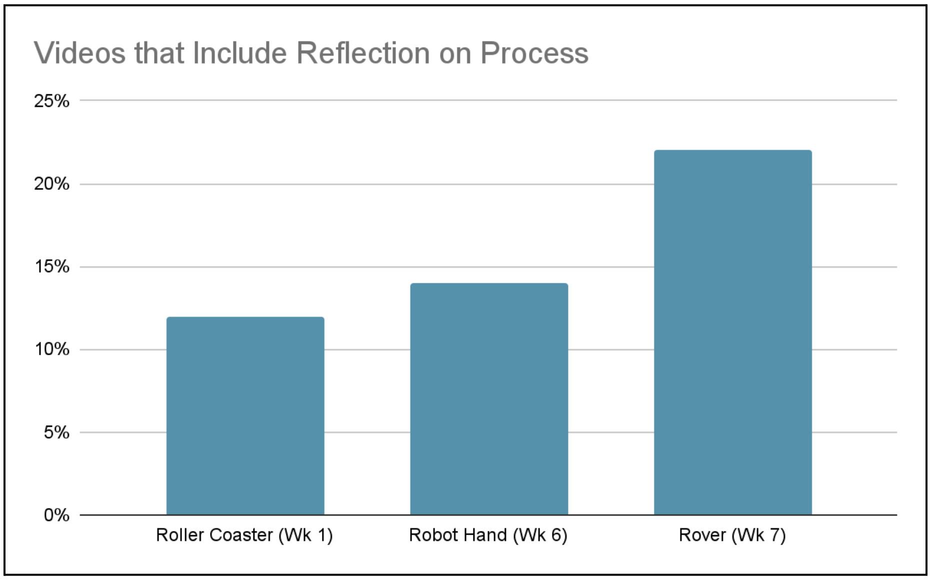

Fig. 3 Percentage of videos that include reflection on the process, sorted by task.

Results: Use of Engineering Design Practices

After the timeline analysis, researchers identified the presence of selected engineering design practices. Examples of student statements for each element in the coding guide are shown in Table 5.

Table 5. Examples of design practices present in student statements

Engineering Design Practice	Example Statements
Category I: Problem Framing	
Design Criteria	*Here is my Roller Coaster that has 1 turn and can successfully land a ball in a cup.* (S29RC); *The Robot Hand needs to pick up the ball to be successful.* (S29Hand)
Context	*The Rover is supposed to transfer rock samples.* (S18Rover); *And here it will pick up the rock sample, which is the ping pong ball.* (S10RH)
Category II: Ideation	
Engineering Graphics	N/A: No videos included this element.
Multiple Solutions	*Let me show you my other models.* (S13Rover)
Category III: Decision-Making	
Science Informed	*In the process of making this, the ball actually didn't gain enough kinetic energy to go over that hill so then I actually made the slope a little bit longer. (S20RC)* *There is a straw at the back to keep it balanced and another straw for less friction.* (S24Rover)
Testing Informed	*The ball kept flying off. I used paper so it could be taller, and the ball would instead go into the cup.* (S30RC) *After a couple of tries I made something else. I used this, and I basically took the ping pong ball and did it like this and then it would hold it up. But then it was too heavy.* Student shows straws holding the ball. *So then I went with this, and I attached something to it. But then again it was too heavy. So then I just used something like this and put it here. And now it goes. This one I made was very lightweight so it moved quicker.* (S13Rover)
Material Properties	*I put a AAA battery because it is lighter than the other battery.* (S27Rover) *I placed a straw in here to cause less friction.* (S22Rover); *In the back, I had to add to add extra cardboard and tape so it can be more durable.* (S10Hand)
Material Processing	*I cut the colored papers into strips. Then I folded the paper into fourths, and then I left the sides of the paper up to create a wall that keeps the ball from falling off the Roller Coaster.* (S7RC) *I used construction paper for my arm and wrapped it around my wrist area so it would stay put. I also put a few extra straws over here for extra support so my hand wouldn't drop down.* (S11Hand) *I poked holes so it can move faster.* (S29Rover) *On the hand, I had to bend each finger, glue on some straws, and thread the string through. Each string I had to make a loop so I can fit my fingers through. As a result, the fingers can bend and move.* (S10Hand)

The frequency of each engineering design practice across engineering activities is shown in Figure 4.

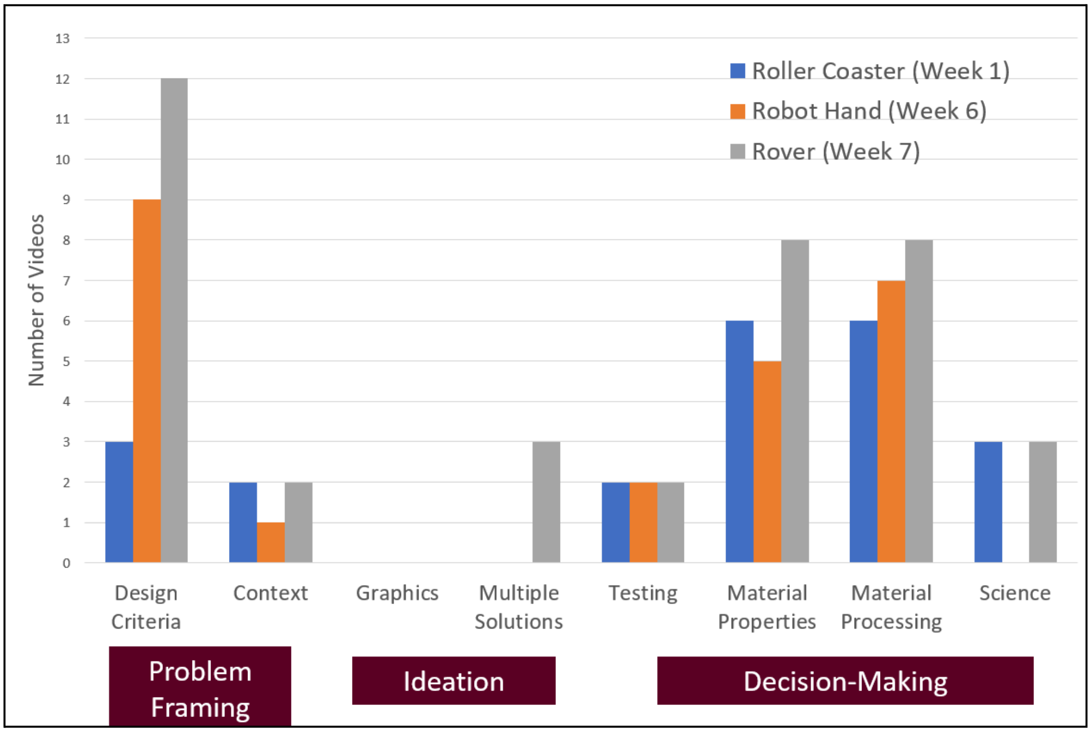

Fig. 4 EDPs present by engineering activity

<u>A Majority Described the Decision-Making Process.</u> The most common EDP present across the videos was decision-making, with 73% of the videos providing insight into making a design decision based on logic or experience, typically focused on material properties or processing. Only six (13%) of the videos described testing, and all of those focused on a trial-and-error approach. For example, one student explained how "after a couple of tries, I made something else. I used this, and I basically took the ping pong ball and did it like this, and then it would hold it up. But then it was too heavy. So then I went with this, and I attached something to it. And now it goes" (S13Rover). This tinkering approach was also evident in the videos that discussed material properties (45%) and material processing (40%). For example, "I decided to improve my roller coaster by making the base thicker with cardboard as it kept collapsing" (S5RC) or "I used construction paper for my arm and wrapped it around my wrist area because it kept falling. I also put a few extra straws on the inside and outside over here for extra support so my hand wouldn't drop down" (S21Hand).

<u>Discussion of Problem-Framing Focused on Design Criteria.</u> The second most common design practice evident in students' explanations (53%) was problem-framing. All videos that included problem framing explained the design criteria. The discussion of design criteria often appeared before testing the product. Students would first explain the necessary design (e.g., "My rover is able to travel the required 1-foot distance" (S9Rover)) before demonstrating the product (e.g., showing the Rover traveling the 1-foot distance). However, students rarely connected the product to the larger context. Only five of the ninety videos, spread across the three activities, referred to

the purpose of the model. For example, one student stated, "The Rover is supposed to transfer rock samples on the Moon" (S18Rover). While the *Mission to Moon* handouts provided a problem statement at the top of the handout and the instructional videos emphasized the larger context of the design challenge, students rarely referred to these in their videos.

Ideation is Lacking. The use of ideation, including engineering graphics and multiple solutions, was rarely seen in the videos. Only three of the student videos referred to developing multiple solutions, defined as building and testing at least two models to solve the problem. One of the students demonstrated two models during the assessment video (A13Rover). All three of these videos were during the Rover activity, which was the last week in the series.

The Design Activity Appears to Influence Use of Design Practices. Overall, more design practices were evident in the week 7 Rover challenge. Table 6 highlights the increase in the number of student videos that included design practices as well as the total number of design practices across the assessment videos. The results indicate very little change from week 1 to week 6 and a large jump in week 7. Similar results were found when comparing the EDPs at the individual student level. Only 20% of the students included more design practices in week 1 (Roller Coaster) compared to week 6 (Robot Hand), while 50% improved from week 1 to 7 (Rover). In other words, many students *decreased* in performance from the Roller Coaster to the Robot Hand and then improved during the final week with the Rover.

Table 6. Progression of EPDs across engineering activities

Week	No. of Videos with at least one reference to an EDP	Total EDP Coded across Videos
Roller Coaster (Week 1)	12	32
Robot Hand (Week 6)	14	32
Rover (Week 7)	21	53

Variability in Solution Models Appears to be Related to the Task. Figure 5 shows examples of final projects featured in the assessment videos. The students were working from home, so they were unlikely to see other students' projects during the building phase. Thus, any similarities are likely a result of the project instructions and design constraints. Comparing the projects, the *Roller Coaste*r and *Robot Hand* projects look most similar across student videos. Despite using the fewest materials, the *Rover* activity had the greatest variety in designs. Additionally, the students often personified the rover in the videos. For example, one student encouraged their rover during the testing saying, "You can do it! Oh no. Alright, there it is moving again. Yay, you did it!"

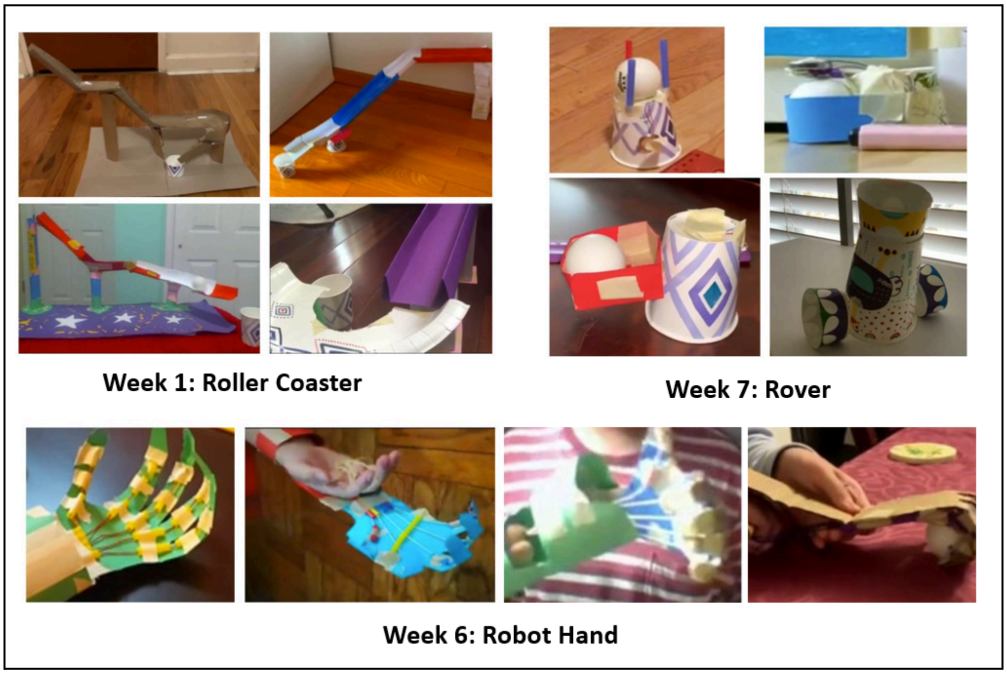

Fig. 5 Variability in designs across engineering activities

Discussion

Product versus Process

Researchers have raised a concern that engineering instruction via design challenges may shift students' focus toward the product rather than engineering practices [6]. This study provides additional evidence that the product of the design challenge is the primary focus for middle school students, and that focus often loses connection to the greater context of the design challenge. All 90 student assessment videos included a product demonstration, but only 52% reflected on the design process, despite explicit prompting to do so. However, students improved their inclusion of design practices over time with 40% in week 1 compared to 70% in week 7. This progression suggests that middle school students may develop targeted design practices through repeated exposure and practice, teacher instruction, increased familiarity with design challenges over time, viewing other students' videos, etc.

However, progress was not equally distributed across reflective elements. Students were more likely to demonstrate meeting design constraints; practices related to problem framing and ideation were rare. This uneven progress may reflect the relative complexity of these practices or their abstract nature, which could be more challenging for middle school students to articulate. The timing of the assessment videos, created after product completion, may have influenced students' focus on the final product rather than the design process. Future studies could incorporate ongoing reflection throughout the design process to capture students' thinking at various stages. Educators also need to develop strategies to help students articulate and reflect on these earlier stages of the design process, even after product completion. More work is needed on the role of context in design challenges. While the program's intent was to engage students with real issues involved in traveling and working on the moon, students ultimately worked with construction paper, straws, string, and other common craft materials, and they rarely made connections back to the original context. Little is known about how "authentic" design tasks should be to optimize the learning of design practices.

Tinkering versus Systematic Testing

The FPEL describes engineering design as a "systematic" process [5] with expectations for students to optimize the final working model in meeting design criteria. In contrast, all students in this study used a tinkering or trial-and-error approach when reflecting on their decision-making and testing approach. In one sense, tinkering is unsurprising and may be appropriate for students of this age. Design challenges frequently require students to use materials in ways inconsistent with their original purposes (e.g., using spaghetti and marshmallows to build a tower or toothpicks or straws to build a bridge). While students' familiarity with these materials may vary, most lack experience applying even familiar materials in the specific contexts posed by these challenges. Additionally, many students have limited experience creating novel structures. Childhood building sets, for instance, often provide detailed plans to follow and pieces pre-designed for specific roles in the final product.

Given these factors, it is reasonable to expect that students might find tinkering a more effective strategy than creating formal plans before building, particularly in the absence of prior knowledge. Professional engineers, in contrast, approach their work systematically because they draw on extensive experience and advanced skills, such as abstract thinking and visualizing designs through written plans, computational modeling, and predictive analysis tools [20].

This raises a critical question: How can educators teach students to adopt a more systematic approach to design challenges? Research has consistently shown that students tend to skip the planning phase before building [32] [33], a behavior that aligns with the challenges discussed here. One potential solution is to incorporate a preliminary phase where students engage in free exploration of materials and partial building. This phase would allow students to experiment with developing models, gather performance data, and analyze that data before making changes. Additionally, design challenges could be structured so that the final deliverable is a completed plan created after initial tinkering and model testing. Such a "flipped engineering" approach more closely matches how children learn (particularly when they lack the prior knowledge that professional engineers employ) and more accurately reflects the goal of engineering (the design itself).

Impact of Design Activity

Counter to expectations, students did not gradually increase their inclusion of design practices over time. Student performance decreased with the *Robot Hand* task in week 6, and increased in week 7 with the *Rover* task. This suggests that the nature of the task itself may influence the practices students employ. For instance, students rarely developed multiple solutions; when they did, it occurred exclusively during the Rover activity.

The *Rover* task had unique characteristics that likely encouraged innovative problem-solving. It used minimal materials, featured open-ended constraints, and resulted in the greatest variability in designs. A key challenge in this activity was optimizing the placement of the battery and motor to achieve forward motion. Since building a rover model required relatively little time, students had the opportunity to construct multiple iterations to refine their designs. As one student remarked, "The rover took me quite a few tries!" (S13Rover). This combination of short build time, open-ended constraints, and a focus on optimization provided students with more opportunities to engage in decision-making, prototyping, and other core aspects of the design process.

In contrast, the *Roller Coaster* had open-ended design constraints that should have resulted in greater variability of solutions. However, examples of roller coasters and tips in the instructional video likely influenced student design solutions. Additionally, the building of one model required extensive time and materials, likely limiting improvement efforts to tweaking the model instead of major design changes. The *Robot Hand* task included a step-by-step instructional video that demonstrated how to build the hand. This task was also time-intensive, requiring significant effort to thread strings through straws to create functional movement. As a result, students were less likely to construct multiple models.

Therefore, despite all program activities involving the engineering design process, the activities themselves have different affordances and constraints. The design constraints, the number and type of materials, the need for and specificity of instructions, and the time required to develop a testable model appear to influence what practices students employ. Considering these factors may enable more informed decision-making about what challenges to use, and how to structure them. As illustrated in Figure 6, design challenges can be differentiated based on two dimensions: the diversity of potential outcomes and the number of iterations required to achieve success. Tasks high in both dimensions are more likely to promote the use of iterative design processes, encouraging students to engage more deeply with engineering practices. Conversely, tasks that score low in both dimensions resemble "crafting" activities, where success can be achieved without fully employing engineering practices.

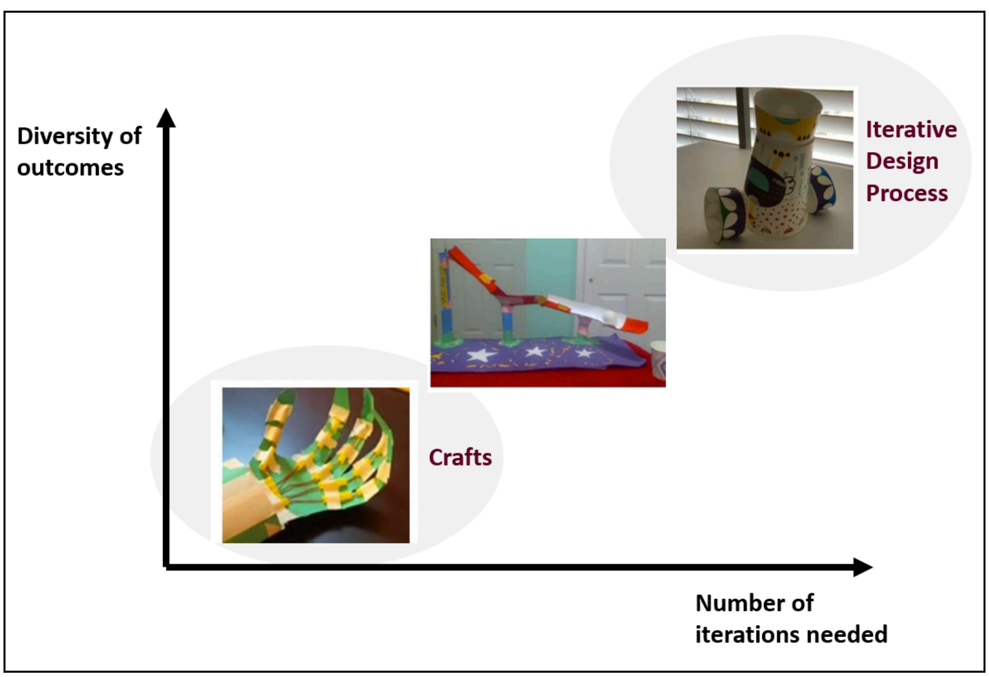

Fig. 6 Selection of engineering activity

Conclusion

Engineering design challenges are not created equally, and tinkering is the default problem-solving method that middle school students employ. Given the knowledge required to generate successful designs in advance of working with materials, tinkering should be viewed as a legitimate problem-solving method for students of this age. This will require engineering design challenges to be redesigned to allow/encourage tinkering and use what is learned to inform a final design. Such a structure would have the added benefit of shifting focus toward the production of a design and reducing the focus on the production of a craft-like model. Middle school students can learn and employ some engineering practices, and the extent to which they do appear to be related to a number of factors, including their developmental level, prior experience with such challenges, and the task itself, particularly the number of iterations required for success and the variability of outcomes that are possible. Some practices, such as developing multiple solutions, may be enhanced for middle school students by altering the task so that multiple iterations are needed and a high diversity of outcomes is possible. Other practices, such as systematic testing and the use of engineering graphics, were consistently low. These practices may be more challenging for students of this age to learn and apply, or they may require different teaching methods.

Given these findings, far more understanding about developmentally appropriate learning outcomes for engineering practices and content across the K-12 grades is needed. Because engineering design challenges are not equally associated with the use of specific engineering practices, careful consideration also needs to be given to the features, affordances, and limitations of the engineering activities employed, and in what order they are used. This will enable a more intentional learning progression of engineering practices that takes into account the age and abilities of the learner and the desired outcomes for a high-quality engineering education.

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Appendix. Final Coding Guide

Background Information

A. Video Identifier Number:
B. Student Gender: M / F

Timeline Analysis

Place a marker for each element: process, product showcase, and product testing.

A. Total video length (seconds):
B. Total time on process (seconds):
C. Total time on product showcase (seconds):
D. Total time on product testing (seconds):

General Observations

Mark if the following are present:

- ◻ Demonstration of meeting design criteria
- ◻ Video in student's home
- ◻ Involvement of family members
- ◻ Entertainment: The student makes an effort to make the video entertaining, such as using filters or stickers.
- ◻ Off-Topic: The majority of the video is not related to the engineering activity.

Notes:

Analysis of Discussion of Engineering Design Process

Mark if the following are present:

A. Problem-Framing
   - ◻ Design Criteria: Student shows an understanding that the product needs to meet specific design criteria to solve a problem.
   - ◻ Context: Student describes the larger context of the problem being solved.

B. Ideation
   - ◻ Engineering Graphics: Student refers to or shows an engineering sketch of a design idea.
   - ◻ Multiple Solutions: Student describes brainstorming multiple ideas for solving the problem.

C. Decision-Making
   - ◻ Science-Informed: Student describes applying scientific knowledge to inform a design decision.
   - ◻ Testing-Informed: Student describes the process of testing the model to gather data to improve the design.
   - ◻ Material Properties: Student describes selecting materials to meet design criteria. Answers the question, why did you choose a material for the model?
   - ◻ Material Processing: Student describes the process of manipulating materials to meet design criteria. Answers the question, how did you manipulate the materials to create the model?

Notes: