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Assessing the Engineering Identity of Elementary School Students Through the Application of a Critical Thinking Skills Framework: Pre-college Research to Practice

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Introduction

Human identities, specifically student identities, are constantly developing and changing as experiences allow for exposure and reflection [1]. An individual's identity is not unitary - identities consist of both personal components and a variety of social components working in tandem to shape an individual's sense of self. This sense of self, composed by identifying as a part of a variety of different "groups" is shaped through constant relationships and comparisons to others, as well as personal experiences [2].

Identity is complex and interconnected, and no single identity can define a person. STEM identity (or more specifically for the following study, engineering identity) that students possess will be the main focus of this paper. For the purpose of this study, a student's engineering identity will be described as "the ability to see oneself as an engineer." The framework for defining engineering identity for this study is built upon the Model of Science Identity developed by Heidi Carlone and Angela Johnson [3] to measure STEM identity of undergraduate students of color, using evidence of the application of critical thinking skills [3], [4]. In previous studies, Carlone and Johnson's framework was primarily used to assess science identity perception and development. For this proposed study, the focus of the research will emphasize student engineering identity development in an intermediate elementary classroom with students in grade 4.

Recognizing the importance of student identities and their development throughout a student's educational career, I seek insight into the following question:

1. How does participation in an engineering unit utilizing the engineering design process allow students to authentically engage in critical thinking skills as an authentic engineering performance?

Literature Review

STEM Identity Development

Student identities (specifically STEM identities) are constantly changing and developing throughout adolescence, influenced by a variety of factors, including classroom settings, educator perceptions, and peer interactions [5]. Particularly relevant to this study and the development of STEM identity, Carlone and Johnson developed a model of science identity based on the experiences of undergraduate female students of color [3]. Focusing on 15 women of varying racial and ethnic identities at a small university, Carlone & Johnson conducted interviews with participants about their experiences in science spaces, leaning heavily on the *recognition* component of science identity. As a result, Carlone and Johnson indicated three components of internalized science identity: *performance*, *recognition*, and *competence*. *Competence* involves demonstrating skill and ability, performance pertains to speaking, interacting, and presenting oneself in ways associated with the subject, and *recognition* refers to being acknowledged by oneself and others as the kind of person who engages in the subject [3].

This framework for analyzing student science identity development has since been applied numerous times to studies focusing on students of a variety of different ages and across STEM disciplines. For example, Kim et al. [5] focused on STEM identity rather than just science identity for middle and high school students. In their review of current research regarding female students' STEM identities, researchers Kim, Sinatra, and Seyranian [5] focused heavily on social identity theory, assessing how social environments impact STEM identity for female students in middle and high school settings. Here, the authors define social identity as "... the extent to which individuals see themselves in terms of their membership in a social group" [5]. It is important to note that the authors distinguish between personal identity (how an individual sees themselves) and social identity. In their review of current research on STEM identity, the authors analyzed 47 different empirical studies that took place in the United States with an emphasis on female participants. Similar to Carlone and Johnson [3], the review of the literature revealed the domain of *recognition* as a key component of student identity development in science. Similar findings were found when assessing STEM identity. STEM identity is influenced by two key factors: first, a feeling of *belonging* and self-acceptance within a STEM environment, and second, a feeling of *recognition* by peers as an individual who belongs in the STEM space [5]. Expanding on these factors influencing STEM identity for middle and high school female-identifying students, the authors found that beginning as young as 6th grade, peer interactions and perceptions greatly influenced student career and course interest and pursuits [5].

Identity development progresses throughout a student's school experiences, beginning much earlier than the undergraduate levels assessed by many STEM identity studies, an important task, considering the findings from Kim, et al. [5] In fact, a study by Bandura et al. [6] demonstrated the impact of perceived self-efficacy in young children and their future career aspirations. This early development is impacted by a variety of factors, such as academic performance, peer and teacher *recognition*, and acceptance of self within a field [5].

Research shows that engagement and interest in STEM subjects decreases in certain identity groups beginning in middle school, despite a closing of the STEM achievement gap in terms of gender. [7], [8]. In fact, societal and classroom norms often influence the development of a student's STEM identities differently, depending on their racial and/or gender identity [5].

Multiple studies have found that greater enrollment in STEM courses in high school and college does not equate to similar representation of female students in STEM careers [9]. For example, female-identifying high school students make up greater enrollment numbers in science courses and higher test scores in science subjects than their male-identifying classmates, yet female-identifying professionals are disproportionately represented in nearly all STEM fields and university reports reveal that there are fewer female-identifying STEM majors than male-identifying STEM majors [10]. This leads to ongoing questions centered around gender and science, engineering, math, and technology identity. Specific to this study is the question of whether this epidemic of disproportionate gender representations in the STEM fields is reflective of high school and undergraduate experience or rooted in something deeper, beginning to develop in earlier years of an individual's education and experiences, at a crucial time of identity development.

STEM Identity Development - Elementary School Students

Despite the growing amount of literature and empirical studies on student STEM identities, there is still a gap in the understanding of the development of STEM identity for elementary school-age students. Yet, these students are at a critical time in their development for identity formation [5]. In response, Carlone [11] conducted longitudinal case studies focusing on STEM identity for three students transitioning from elementary to middle school. Applying their 2007 framework [3], they confirmed that the social identities of students and their various intersecting identities (race, gender, class, etc.) impact the development of science identities in students as young as fourth grade. Carlone et al., [11, p.864] note that "school science is subject to strong institutional and cultural narratives…" but that hope remains for disrupting these "prototypical" practices during the elementary-age years, especially when applying the science and engineering practices from the Next Generation Science Standards (NGSS) [11], [12].

Building on Carlone et al. [3], [11], Paul et al. [13] developed and implemented the RIS-E and RIS-STEM surveys to measure engineering and STEM identity development. While the RIS-E and RIS-STEM surveys from Paul et al. [13] are useful when evaluating a student's comprehensive STEM identity (*performance*, *competence*, and *recognition*,) it provides more of a preliminary look at what influences student STEM identities than a more focused case study. Paul et al. [13] is a critical component of the literature on STEM identity for elementary school students, because it provides a detailed measurement tool appropriate for use with younger students. Through two studies (one focusing on engineering identity and one on STEM identity), Paul et al. [13] developed their RIS-E and RIS-STEM surveys to measure four components of identity, using the original science framework from Carlone and Johnson [13], [3]. Similarly to previous studies focusing on science, engineering, and/or STEM identity as a whole, Paul et al. [13] divided identity into different domains: *competence*, *interest*, *self-recognition*, and *recognition* by others. In their study on STEM and engineering identity development, Paul et al. [13] combined *competence* and *performance* into a single category of identity development, emphasizing *recognition* and *interest* instead. Carlone and Johnson [3] also emphasized the domain of *recognition* in their 2007 study, and even noted that the study lacked insights regarding how students *perform* in science, and how this impacts their science identity.

Recognizing this gap in the research on science identity focusing on performance and my desire to look at engineering rather than science, I turned to Putra, et al. [4] which focused on the application of *critical thinking skills* (CTS) during the *engineering design process* (EDP). While this study does not specifically emphasize an analysis of student science or STEM identity domains like Carlone and Johnson [3] and Paul et al. [13], the authors provide insight regarding how to measure student *performance* (an identity domain) of critical-thinking as a result of engaging in the engineering design process.

Critical Thinking and the Engineering Design Process

Relevant to this study, Putra et al. [13] researched student performance of critical thinking skills (CTS) within the context of an engineering design project. Putra et al. [13, p. 142] summarize critical thinking as "...a cognitive process involving reasonable reflective thinking to develop a decision based on the problem faced by a person." Specifically, they drew on the cognitive skills outlined by the American Philosophical Association (APA) from 1990, as cited in Ernst & Monroe [14] in Table 1:

Table 1 *Critical Thinking Skills, Defined*

Skill	Action Items/Demonstration Examples
Interpretation	Categorization, decoding significance, clarifying meaning
Analysis	Examining ideas, identifying and analyzing arguments
Evaluation	Assessing claims and arguments
Inference	Querying evidence, conjecturing alternatives, drawing conclusions
Explanation	Stating results, justifying procedures, presenting arguments
Self-regulation	Self-examination, self-correction

They applied this critical thinking skills framework to measure the CTS performance of high school physics students engaged in the engineering design process (EDP,) Putra et al. [4] looked for instances of CTS across the engineering design process, ultimately identifying when in the process students performed certain CTS most frequently and effectively (high or low performance.) Critical thinking skill was measured as being applied at a "high" or "low" level throughout the process. Putra et al. [4] concluded that the EDP supports students' development of critical thinking skills and thus their engineering performance.

The decision of the researchers to assess the performance of CTS throughout the engineering design process was due to the nature of both CTS and the EDP to follow "cycle models" of learning [4, p. 142-143]. Putra et al. [4] point out that the engineering design process is often taught through a cyclical learning process, requiring a similar learning process often found in the application of CTS. In fact, Putra et al. [4] assert that one way to practice CTS is to follow a "cycle learning process" including defining a problem, developing a solution, and reflective thinking - processes which are found explicitly in many engineering design processes [4, p. 142-143].

The engineering design process is a set of "steps" or "stages" followed by engineers in order to solve a problem [15]. Similarly to scientific methods, there is no single agreed-upon EDP, and the processes vary specific to the nature of the problem under investigation. Regardless of the specific steps and stages used when applying an EDP, K-12 engineering design processes typically emphasize on designing solutions through systematic processes involving prototyping and testing (experimentation) in collaborative environments throughout three general phases [15]: (i) Problem identification (define and learn), (ii) Designing and prototyping solutions, and (iii) Testing. The design of solutions through a streamlined process begins with *identifying the problem* that is to be solved (International Technology Education Association (ITEA), 1996) Arik & Topcu [15]. In their study, Putra et al. [4] name this step "Define." Often included in this step is the conduction of background research on the topic, although some EDP separate these processes into separate steps [15]. Putra et al. [4] names this second substep of problem identification as "Learn." Once a problem has been identified and researched, the second phase emphasizes the designing and prototyping of possible solutions [15]. Again, Putra et al. [4] break this phase down into two steps - *Plan* and *Build.* In these steps, students worked in small groups to brainstorm possible solutions, eventually *building* and modeling their designs. Finally, most engineering design processes conclude with a third phase requiring testing of designs and a formal decision on the most appropriate solution based on the tests [15]. The EDP used by Putra et al. [4] followed all three phases of the design process, broken into the following steps: Define, Learn, Plan, Try, Test, and Decide. Students in their study worked through these steps to solve a problem while Putra et al. [4] looked for evidence of CTS. A table connecting the three general steps of all design processes from Arik & Topçu, [15] with the design process used by Putra et al. [4] and the process used for this study can be found in Table 2:

Table 2 *Critical Thinking Skills and the Engineering Design Process*

Critical Thinking Skill	Code	Example of Skill in EDP in Putra et al. [4]	Stage(s) Displayed Most Frequently in the Engineering Design Process
Analyzing	CTS_A	Examined an idea with argumentation	Try Test
Interpretation	CTS_I	Categorized information & clarified meaning	Define
Inferencing	CTS_IN	Developed multiple solutions based on relationships between variables	Plan
Self-regulating	CTS_S	Reflecting on role; self-correcting	Plan Decide
Explaining	CTS_E	Presenting & justifying an argument	Learn
Evaluating	CTS_EV	Assessing claims, supported with evidence	Try Test

Regardless of the specific steps used, the engineering design process requires a student to apply critical thinking skills, a crucial 21st century skill [6]. The Paul-Elder Critical Thinking Model states that to improve the quality of one's thinking, intellectual standards, such as clarity and precision, must be applied to elements of reasoning, such as asking questions and making inferences, which are key stages of the engineering design process [17. Therefore, when a student applies these critical thinking skills, I assert that they are *performing* as an engineer, thus advancing one of the domains of identity described by Carlone and Johnson [3]. Putra et al. [4] sought to uncover how the EDP supports student's use of CTS, which they state are relevant skills needed to complete the EDP. Therefore, I suggest that the engineering/STEM identity domain of *performance* can be measured in the EDP through the observation of CTS.

As a result of their study, Putra et al. [4] found that certain CTS were more prevalent at various stages of the EDP, summarized in Table 2 above.

Critical Thinking and Engineering Identity

The following study combines aspects of the science identity framework from Carlone and Johnson [3] (adapted by Paul et al. [3] to encompass engineering identity) with the essential components of critical thinking from Putra et al. [4]. Of the three identity components identified by Carlone & Johnson [4], this study focuses on the single identity component of "performance," specifically "performance as engineers." This will be measured during an engineering design unit using the critical thinking framework outlined above by Putra et al. [4]. In summary, students will be observed for displaying evidence of varying levels of critical thinking skills within an engineering design process in an effort to gain insight regarding the development of their engineering identity through the component of "performance."

Study

This study connects the *performance* aspect of identity from Carlone and Johnson [3] to engineering, measured through demonstration of CTS within the EDP. To do this, I explored the engagement in critical thinking skills (CTS) from Putra et al. [4] of students in small groups working through the engineering design process along with their responses to the RIS-E assessment. Supported with a constructive belief system that emphasizes the subjective experiences of an individual within the context of a STEM classroom, this study utilized a multiple case study [18] This method allows for an in-depth exploration to begin to develop an understanding of how engagement in an engineering unit centered around the engineering design process impacts student engineering identities, namely the identity domain of performance, made evident through the application of critical thinking skills.

Context

The study took place in a suburban, public, midwestern elementary school (grades K - 5) within my STEM specialist classroom. At this specific school, students rotate through five different specialist classes (art, physical education, music, STEM, and media/library) on a five-day cycle, attending each class for 50 minutes once every five school days.

At this school, students begin participating in STEM education specialist courses at the beginning of kindergarten, and continue attending every five days through the course of their elementary school career, each year taught by the same instructor. This provides for streamlined instruction based on one instructor's ontological beliefs throughout the student's elementary academic career. Within this particular classroom, I strive to provide situational learning environments that embody a constructivist belief system beginning in kindergarten. In order to accomplish this, students follow a year-long curriculum plan adopted and developed by the instructor composed of four or five engineering design projects (units) once they begin third grade, adapted to provide students with opportunities to practice critical thinking skills embedded within the engineering design process. Beginning in kindergarten, students follow a variation of the engineering design process (Figure 1). Critical thinking skills (*analyzing, interpreting, inference, self-regulation, explanation,* and *evaluation*) are expected to be applied at various phases in the process, but had not been explicitly tied to the EDP I teach from prior to this study.

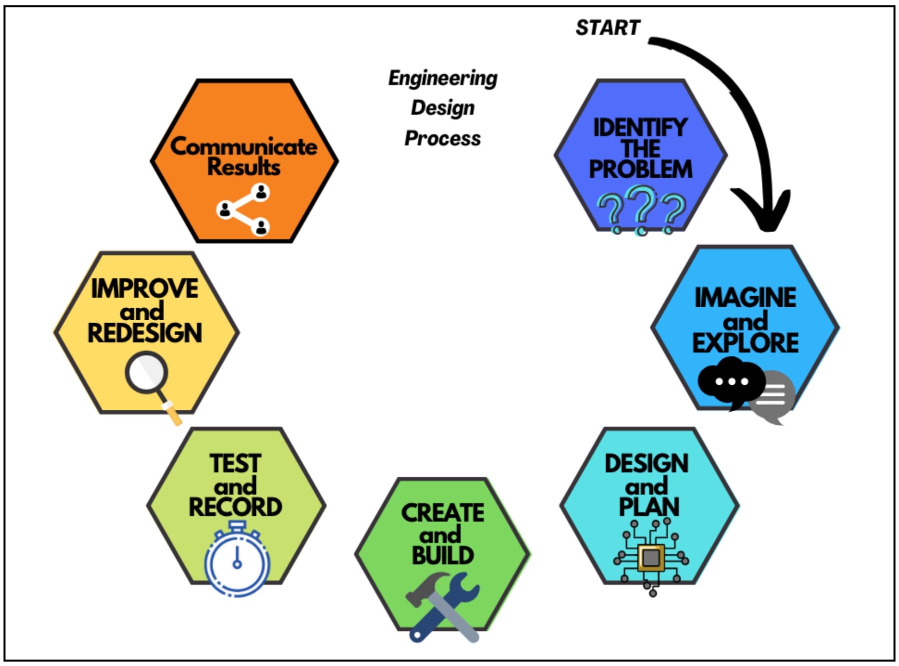

Figure 1 *Engineering Design Process Used*

The EDP used in this study still follows the three main phases of most engineering design processes (defining problems, designing and evaluating solutions, and optimizing a solution) explained by Arik and Topçu [15] and follows similar steps and stages to the design processes used by Putra et al. [4]. A comparison of the two processes can be found in Table 3. It was decided not to adopt the same EDP as Putra et al. [4] because the existing process in my classroom where the research was conducted has been used with students for multiple years, and is used across the school community.

Table 3 *Comparing Different Engineering Design Processes*

Phase Outlined by NGSS, in Arik & Topçu [15]	**Name of Step/Stage in Putra et al. [4]**	**Name of Step & Stage Number in *This Study***
Defining Problems	Define	Stage 1: Identify the Problem
Defining Problems	Learn	Stage 2: Imagine & Explore
Evaluating Solutions	Plan	Stage 3: Design & Plan
Evaluating Solutions	Try	Stage 4: Build
Evaluating Solutions	Test	Stage 5: Test
Optimizing a Solution	Decide	Stage 6: Redesign Stage 7: Communicate Results

Study Details

Working within these parameters, the study took place over the course of seven weeks, each week consisting of one 50-minute fourth grade STEM class, with one lesson planned for each class period. Audio and/or video data was collected at four of the seven class sessions from small groups and stored until completion of the study. The fourth-grade students were engaged in their final unit of the school year, which focused on renewable energy through the study of wind turbines. Using a variety of resources from all age-levels of the KidWind Curriculum, students were tasked with working through the engineering design process to create blades for a wind turbine that were able to rotate a minimum of 30 times per minute (RPM) [19].

Throughout each lesson, students kept a digital lab notebook (see appendices A - D) using the app, Notability. Students were always provided with the option of completing their STEM writing and sketching on paper copies, but were asked to upload images of their work to their digital Notability notebook at the end of each class session. Lessons were scaffolded throughout the unit to begin with just one step of the design process and one relevant lab notebook page, and this amount was gradually increased throughout the unit as students demonstrated greater familiarity with the process and the connection between writing, recording data, and sketching within the design process. A more detailed view of the unit can be found in Table 4.

Table 4 *Lesson Summary of KidWind Influenced Unit*

Lesson #	EDP Focus	Expected CTS	Lesson Summary	Data Collection Methods	Related Student Documents
1	Identify the Problem	Analyzing (CTS_A) - Students analyze the background information and identify a problem that needs to be solved	Students engaged in a whole-class read aloud, "The Boy Who Harnessed the Wind" to provide context and an aspect of empathy (see “Stanford D-School Design Process”). Students then worked together as a class to formally identify the problem.	Group Writing Reflection; Pre RIS-E Survey	Appendix A - Planning Sheet
2	Imagine & Explore	Interpretation (CTS_I) students categorized information and formed new understandings based on provided information	Beginning in a large group, students began discussing the attributes of images of wind turbines displayed on the screen, discussing the geometry the recognized. Next, students participated in the "Mini Windmill" lesson from the elementary KidWind Curriculum. Finally, students participated in a five-minute, low-stakes sketching exercise to try and explain how a wind turbine blade "catches" the wind and creates electricity.	Whole-Class Video Recording	Appendix B - Imagine & Explore
3	Design & Plan	Explanation (CTS_E) - Why their design choices were relevant; Self-Regulation (CTS_S) - Making decisions in a group environment; Inferencing (CTS_IN) - develop multiple solutions based on previous knowledge	Students reviewed their sketches from the previous week and engaged in a whole group discussion regarding how wind turbine blades help capture the kinetic energy from the wind. Students were broken into assigned small groups where they began creating a plan on the same document used to identify the problem during the first lesson.	Audio Recording	Appendix A - Planning Sheet

4	Create & Build	Self-Regulation (CTS_S) - performing in a way to meet their goal within a collaborative setting	Students reflected upon their collaborative planning sheet(s) (which was required to have labels, supply lists, and the total cost of materials) to go "shopping" for supplies and began building in small groups. Creations were stored until the next lesson. Students used any remaining time to read articles and books related to wind energy.	Video/Audio Recording	Appendix A - Planning Sheet
5	Test & Record	Self-Regulation (CTS_S) - performing in a way to meet their goal within a collaborative setting	Students attached their blades to a KidWind turbine base and worked in groups to record data regarding how many rotations their turbine completed in 30 - 60 seconds.	Video/Audio Recording	Appendix C - Data Sheet
6	Improve & Redesign	Analyzing (CTS_A) ; Explanation (CTS_E); Evaluation (CTS_Ev); (CTS_IN) - students analyze their data to make informed decisions, explaining with evidence the redesign choices they make	Students analyzed their data sheets from the last lesson to guide discussions in the small groups guided by a reflection form with sentence stems and a "SWOT Analysis" handout. Groups created a second iteration of their planning sheets.	Audio Recording	Appendix D - Reflection Form Appendix E - SWOT Analysis
7	Rebuild, Retest, & Communicate Results	Impacted by steps 5 & 6 of EDP	Students applied their new knowledge of how wind energy can move physical objects (the blades) based on the design and materials used to rebuild and retest a second prototype of wind turbine blades. Students discussed results in small groups.	Group Writing Reflection; Post RIS-E Survey	Appendix C - Data Sheet Appendix D - Reflection Form Appendix E - SWOT Analysis Handout

Participants

Four small groups of students ranging in size from two to four students each participated in this case study. However, due to student absences throughout the course of the study, only two of the groups were present for all five lessons. Therefore, this study focuses only on these two groups of students. Each of the participants had been enrolled at this school for at least three years at the time of the study, meaning they had participated in the STEM specialist class for at least that same length of time. All of the participants self-identified as female, a circumstance dictated solely by which recruited participants (the entire 4th grade population at the school) returned their permission slips. At the beginning of the unit, students completed a demographic survey where they self-identified their gender and race (Table 5).

Table 5 *Self-Identified Demographics of Study Participants*

Pseudonym	Group #	Gender	Race	Data Collection Participation
Annie*	1	Girl	White	Video & Audio; Pre/Post RIS-E Surveys
Sarah*	1	Girl	Black	Video & Audio; Pre/Post RIS-E Surveys
Layla*	2	Girl	White	Video & Audio; Pre/Post RIS-E Surveys
Maddie*	2	Girl	White	Video & Audio; Pre/Post RIS-E Surveys
Megan*	2	Girl	White	Video & Audio; Pre/Post RIS-E Surveys

*** all names are pseudonyms**

Data Collection

Given the framing of this study that students act (perform) as an engineer when they demonstrate critical thinking skills at various steps of the engineering design process, thus developing aspects of their STEM identity, data was collected through observation of small groups as they engaged in the engineering activities. The first two lessons were recorded via video, but were structured around whole-class, teacher-directed instruction, making it difficult to discern how individual students responded and reacted during these steps. Lessons 3 -7 included audio and video recordings of student groups, beginning at the “design and plan” step through the improve, redesign, and retest steps of the process (Tables 3 and 4). In order to provide clarity of the student discourse on recordings (often audio was detectable but video footage was obstructed, student work samples were collected for further analysis at the end of the unit, including planning sheets, materials lists, written reflections, and actual blades designed for the challenge.

Data Analysis

While data was collected throughout the entire design process, I narrowed down my focus to steps 3, 4, and 6 (design and plan, build, and redesign) of the EDP due to the quality of data collected and the stronger alignment of these phases with engagement with critical thinking skills. These phases of the engineering design process are the most student-driven and hands-on aspects of the design process.

With the understanding that intermediate elementary-aged students are able to demonstrate levels of performance as engineers through the application of critical thinking skills, this study analyzed student discourse and behaviors in small groups of an engineering design unit, applying the coding system from Putra et al. [4] (Table 2). First, I aligned the CTS skills with the phases of the engineering design process used throughout K-5 STEM at this elementary school (Tables 2 and 3) anticipating when in the EDP students would perform different critical thinking skills (regardless of low vs. high/incomplete vs. complete) based on the findings from Putra et al. [4]. This provided a foundation for analysis of student discourse related to engineering performance through CTS in my own classroom.

Next, I reviewed video and audio recordings from two small groups, documenting when in the EDP various CTS were performed. I applied the various CTS identified in Table 2 to the transcribed discourse in order to document instances of engineering performance related to the application of critical thinking skills. I listened and watched for when students were using language associated with critical thinking skills and the engineering design process (a set of skills they begin practicing in kindergarten?). I also watched for when students initiated an engineering performance (like asking a critical question) but abandoned the performance (e.g. Asking a question such as "What do you think would happen if we turned the blades 90˚? but not answering or pursuing an answer.). I classified student behaviors and discourses displaying CTS as "complete" or "incomplete," whereas Putra et al. [4] titled "incomplete" demonstration of CTS as "low" performance and "complete" demonstration of CTS as "high" performance.

I documented specific examples of the discourse between students to help me better understand when in the engineering design process do students perform ("complete") critical thinking skills, when do students struggle to perform critical thinking skills ("incomplete"). Once instances of performance were identified and documented, I analyzed the organized data for patterns of performance to determine when during the process were students performing as engineers most frequently, and in what ways they were performing.

Findings

Critical Thinking Skills in the Planning & Design Stage of the Engineering Design Process

Data analysis revealed nine CTS performances during the planning and design stages of the EDP, involving four of the six critical thinking skills. Each of these skills were demonstrated at least once by study participants during these stages, and both groups demonstrated the critical thinking skills of *analyzing*, *self-regulating*, *interpreting,* and one group demonstrated the CTS of *explanation* (Table 6).

Table 6 *CTS Performed During Planning & Design Stage of EDP*

Students Performing	Instance Number and Student Performance (What was said or done)	Critical Thinking Skill Performed	Complete or Incomplete?
Annie to Sarah	1A: Annie verbalizes the labels on her plan to her partner as she writes them down	Interpreting	Complete
Annie to Sarah	2A: Annie asks her partner (Sarah) if they should color part of their design to aid in data collection. Sarah gives a non-response.	Self-Regulating	Incomplete
Annie to Sarah	3A: Annie & Sarah discuss whether to use tape or hot glue in various parts of their design	Analyzing	Complete
Maddie to Megan & Layla	4A: Maddie asks her group members what they should do for blade shape	Self-Regulating	Complete
Maddie to Megan & Layla	5A: Maddie asks her group members what they should do for blade shape, group members each have a turn to respond and provide an explanation for their answer	Explanation	Complete
Maddie to Megan & Layla	6A: Maddie starts labeling where to put tape on their design, but then backtracks and asks if her group members agree	Self-Regulating	Incomplete
Megan to Maddie & Layla	7A: Maddie reviews their plan verbally, reiterating what needs to happen to make their design a reality	Analyzing	Complete
Maddie to Megan & Layla	8A: Maddie verbalizes the labels on her plan to her partner as she writes them down	Interpreting	Complete
Maddie, Megan, & Layla	9A: Group members go back and forth discussing possible blade sizes, Maddie provides explanations as her partners give suggestions	Analyzing; Self Regulating	Complete Analyzing, Incomplete self regulation

The CTS of *interpreting,* which involves clarifying and organizing information, was observed by both groups and performed completely. During this "Plan & Build" stage of the EDP, students engaged in a whole-class discussion to help orient themselves to the design challenge, allowing them to then successfully engage in *interpreting* the challenge when they broke into small groups. An example of this discourse can be seen in Excerpt 1:

Except 1: Samples of "Complete" CTS Performed in Planning Stage (Instance 1A, Self-Regulating)

Student Performing	Brief Transcript	Timestamp
Annie to Sarah	(describing plan as she labels) -" here we are using tin foil because it will make the blades stronger"	0:58 - 1:00
Sarah to Annie	"What, what are we using it for...?"	1:01 - 1:02
Annie to Sarah	"To make it have better support!"	1:02 - 1:03

The CTS of *analyzing* was also demonstrated by both groups during this stage of the EDP, always coded as "complete" instances (at least once by each group). An example can be seen from instance 9A, Excerpt 2 below. All instances of "complete" CTS involved a discussion between group members regarding their planning sheets (Appendix A.) The CTS of *analysis* involves using argumentation to support an idea - in both of these instances, participants explained "why" they thought they should use the materials included on their planning sheets, hence the "complete" coding label.

Of the nine identified performances within this stage of the EDP, two were "incomplete", meaning that students began engaging in a CTS but either did not progress through their thinking process verbally or visually (meaning it was hard to discern if they fully executed the skill) or moved on in their conversation without an answer to a posed question. In both instances of "incomplete" CTS performances, the CTS that was partially-observed was *self-regulation*, as seen in Excerpt 2 from instance 9 in Table 6 (also coded as *analysis, complete)*:

Excerpt 2: Samples of "Incomplete" CTS Performed in Planning Stage (Instance 9A, Self-Regulating & Analyzing)

Student Performing	Brief Transcript	Timestamp
Layla to Maddie & Megan	"Do we want it wider or longer?"	2:49 - 2:52
Megan in response to Layla	"5 inches? 6 inches? 7 inches?":	2:52 - 2:53
Maddie, in response to Layla	"I think if it was wider it would be more flimsy."	2:53 - 2:56
Layla, in response to Maddie	(Pauses) "Yeahhh, flimsy..."	2:59-3:01
Layla continues in response to Megan & Maddie	How about 7 by 4? or 5 by 5? because I feel... (gets cut off)	3:02 - 3:05
Maddie to Layla	"No, that's too big. And that's a square and we want a rectangle"	3:05 - 3:09
Megan to Maddie	"Okay. How about 6 by 4. That's 24 inches"	3:10 - 3:14
Layla to Maddie & Megan	(Pauses) "Yeah, 6 by 4."	3:16 - 3:17
Maddie to Megan and Layla	"Okay."	3:17 - 3:18

The discourse in Excerpt 2 demonstrates the "incomplete" CTS of self-regulation, as it is evident that Layla wants to participate, but is unsure how to engage and provide meaningful insights, while Maddie struggles to reflect on her role as a group member working in a collaborative, taking control of the design. This excerpt provides an example of how a teacher being present could have supported Layla's *performance* as an engineer, asking guiding questions and providing space for her to process and share despite Maddie's frequent interjections and opinions, thus fostering the development of her engineering identity. This could be especially beneficial for students who are often not fully heard or have quieter dispositions, possibly having their identities challenged as a result.

Putra et al. [4] explain the CTS of *self-regulation* as a student's ability to reestablish required skills and actions needed to solve a problem, such as self-correcting or reflecting. This finding of incomplete *self-regulation* performances in the *planning and design* stage demonstrates the difficulty elementary school students tend to have when it requires delegating tasks and working in groups without direct instructor supervision, and identifies a specific need to provide opportunities to practice compromising and collaborating when trying to solve a problem.

Inferencing and *evaluating* were the CTS not observed during the "Planning and Design" stage (stage 3) of the EDP, despite being CTS found by Putra et al. [4] during their parallel stages. I expected students to engage in conversations while making their plans, developing multiple solutions both formally (sketched out) and informally (discussed verbally,) part of the CTS of inference detailed by Putra et al. [4]. At the beginning of the "Planning and Design" stage, students were tasked with creating their own design independently, then sharing them with their small groups and combining designs until one was decided upon. This data was not recorded, a missed opportunity for insight regarding these specific CTS.

Critical Thinking Skills in the "Building" Stage of the Engineering Design Process

Data analysis of the "Building" stage of the EDP, students engaged in ten CTS performances, including three of the CTS: *analyzing*, *interpreting*, and *self-regulation* (Table 7). Each of these skills were demonstrated at least once by each group during this stage, and both groups demonstrated the critical thinking skills of *analyzing*, *self-regulating*, *interpreting,* and one group demonstrated the CTS of *explanation* (Table 7).

***Table 7** CTS Performed During "Build" Stage of EDP*

Student Performing	Instance Number and Student Performance (What was said or done)	Critical Thinking Skill Performed	Complete or Incomplete?
Annie	1B: When making a change in real time while building, Annie updates their planning sheet	Analysis	Incomplete
Annie & Sarah	2B: After making updates to their plan, Annie asks Sarah her opinion on the changes. Sarah provides feedback simply with a brief nod. They both begin working to make the plan a reality without speaking much more.	Analysis	Incomplete
Annie	3B: Checks the plan for length of tape needed then proceeds to measure out the matching amount needed, gives it to Sarah to use.	Interpreting	Complete
Annie & Sarah	4B: Line up their blades next to each other to check for size comparison	Analysis	Incomplete
Maddie & Megan	5B: Begin discussing what angle they want their blades to be positioned in the turbine. Maddie suggests 30 degrees, Megan suggests 45, Maddie agrees and they write down 45 on their plan	Analysis	Incomplete
Maddie, Megan, Layla	6B: Maddie delegates tasks to group members, Layla asks if she can be the "decorator" and Megan begins to cut and measure materials	Self-Regulation	Complete
Megan & Maddie	7B: Megan asks for clarification on their plan "do we want the tip of the blade to be 6 [inches] or the side to be 6 [inches]?"	Interpreting	Complete
Megan & Layla	8B: After measuring out their initial blade size, Megan asks her group members if they can change the initial size because she thinks it is too big. "Can we change it to 3 [inches]? 4 [inches] is too big."	Analysis	Complete
Layla	9B: Layla spends a significant time trying to decide how to decorate their design, asking her group members for	Self-Regulation	Complete

	feedback		
Megan to Layla and Maddie	10B: "Am I a good measurement person?" (Waits to be reassured, then continues her task)	Self-regulation	Complete

Of the 10 identified CTS during this stage of the EDP, half of the instances of CTS focused on *analysis*, which Putra et al. [4] explains involves examining ideas with argumentation. For example, Group 1 (Annie and Sarah) were observed frequently checking their planning sheet before and after construction of their actual design, making changes in real-time based on their observations as they began working with the materials, noted in instances 1B, 2B, and 4B in Table 7. According to Putra, et al. [4] this would be classified as the CTS of analysis, as the students in this group were observed frequently referencing their plan and making real-time changes, deemed necessary as they worked through the building process. In fact, 80% of the CTS displayed by this group (Group 1) during the "Building" stage of the engineering design process fall under this specific performance category. However, while Annie & Sarah demonstrated the CTS of analysis, their performance of the CTS was classified as "incomplete," as they offered no reasoning or argumentation for their changes, even to each other, as seen in Excerpt 3, detailing instances 1 and 2B:

Excerpt 3: Samples of "Incomplete" CTS Performed in "Building" Stage (Group 1) (Instance 2B, Analysis)

Student Performing	Brief Transcript	Timestamp
Annie:	Silently makes edits to planning sheet after gathering supplies	0:00 - 0:09
Sarah:	Sits quietly, doesn't engage with supplies, plan, or partner	0:00 - 0:09
Annie to Sarah:	*Shows Sarah their updated planning sheet* Asks: "What do you think?"	0:09 - 0:11

Sarah to Annie:	*Silently nods*	0:11 - 0:13
Annie to Sarah:	Begin building, hands supplies to Sarah	0:13

In this excerpt, Annie asked Sarah her opinion on the changes. Sarah provided feedback simply with a brief, silent nod. They both continued working to make the plan a reality without speaking much more. Annie did not offer an argument or rationale for her changes, and Sarah did not provide any argumentation or explanation for why she agreed or disagreed with the way their original idea and plans were changed, which are critical components of *analyzing* as a CTS (Ernst & Monroe, 2004). Therefore, I categorized these performances as "incomplete." It is important to note, it is possible that one or both girls had a rationale for their decisions but it was not made publicly available.

Group 2 also frequently demonstrates the CTS of *analysis* during the "Building" stage of the EDP. Contrary to Group 1 however, Group 2 often "completed" their analyses of their design as they are building, due to their tendency to give evidence and/or reasoning for wanting to make the design changes they proposed. However, all examples of "complete" analysis were demonstrated by Maddie or Megan, not Layla (see Table 7 and Excerpt 4). For example, within the first two minutes of building, Megan realized that their initial blade size was too big. Rather than just making the change, she first asked her group members if she could make the change, and explained why she thought the change was necessary by holding up her first prototype of a blade. This examination of their original idea (plan) supported with evidence and argumentation is a crucial aspect of the CTS of "analysis."

Excerpt 4 *Sample of "Complete" CTS of Analysis in "Building" Stage (Group 2) (Instance 10B, Self-Regulation)*

Student Performing	Brief Transcript	Timestamp

Megan to Maddie & Layla	"Can we change it to 3? I think 4 is too big [for the turbine stand]" *Shows the first prototype she designed as evidence*	1:56 - 1:58
Maddie to Megan	"Yeah, good point"	1:58 - 1:59
Layla to Megan	"Yeah okay"	1:58 - 1:59

Group 2 also engaged in the CTS of *self-regulating* during the "Building" stage of the EDP. For example, it is in this stage of the EDP that we see Layla fully reflect on her own role within the group, going as far as verbalizing her self-appointed task (decorating) to her group members throughout this entire stage of the process, looking for reassurance (instance 9B, Excerpt 5).

Excerpt 5: Samples of "Incomplete" CTS Performed in "Building" Stage (Group 1) (Instance 9B, Self-Regulation)

Student Performing	Brief Transcript	Timestamp
Layla to Megan & Maddie	(Before they even begin building…) "Can I be the decorator? I want to be the decorator!"	0:27 - 0:29
Megan to Layla	(Once the building process is underway and blades have been cut by Megan) "Okay Layla, you can decorate this one." (Passes Layla a blade)	3:30 - 3:32
Maddie to Layla	"Yeah and have fun with it, this is going to be the best design"	3:32 - 3:35
Layla to Maddie and Megan	(Surrounded herself with markers, ready to draw) "What should I do?"	3:38 - 3:40
Maddie to Layla	"Well we are preventing pollution so maybe like an 'Earth' theme?	3:40 - 3:43
—	Inaudible building by Maddie & Megan; Layla drawing on blades	3:43 - 4:00
Layla to Maddie & Megan	"Yeah, I'm gonna draw planets. Like, Earth will look like an orb like this…	4:00 - 4:08

	what do you think?"	

Not only is Layla reflecting on her role during these instances (a characteristic of the CTS, *self-regulating*) she is also looking for recognition by others, a critical identity domain from Carlone & Johnson and Paul et al., [3], [13].

While the identity domain of *recognition* (both by others and by self) was not a focus of this study, evidence of group members searching for recognition as performing as engineers was evident throughout the "Building" stage for Group 2. The members of Group 2 frequently checked-in with one another, not to keep one another on track, but to ensure that they were viewed as meaningfully contributing to the design challenge and that their performance was recognized. After more than five minutes of working, for example, Megan asked her group members if she was a good "measurement person," a task she took on during the "Building" stage. Layla and Maddie assured her that she was, and Maddie reasserted that Layla was "the decorator." The framework developed by Putra, et. al [4] explains that a high-level performance of self-regulating within the EDP involves self-correction and self-examination. With closer observation of this group overtime, it may be possible to uncover whether or not this desire for approval from others demonstrates this CTS or not, providing an opportunity for future research.

Critical Thinking Skills in the Redesign Stage of the Engineering Design Process

The final stage of the EDP assessed for the performance of CTS during this unit was the "Redesign" stage, titled "Decide" in the literature by Putra et al. [4]. During this stage of the EDP, nine CTS performances were observed overall, including all six CTS (Table 8).

Table 8 *CTS Performed During "Redesign" Stage of EDP*

Student Performing	Instance Number and Student Performance (What was said or done)	Critical Thinking Skill Performed	Complete or Incomplete?
Annie to Sarah	1C: Annie tells Sarah what change she thinks they should make (more blades) and then flips through their data collection sheet looking for evidence to explain why.	Evaluation	Complete
Annie to Sarah	2C: Annie makes changes to their plan while verbalizing the changes she is making to Sarah. She begins by sketching out their first design as it looked while they were testing. As she modifies their new plan, she confirms the design with Sarah	Evaluation	Complete
Annie to Sarah	3C: States that they should have pointed blades instead of squares, indicating the success another group had with this design	Evaluation & Explanation	Complete
Maddie to Megan & Layla	4C: *Begins reviewing previous plan and budget before bringing it up to her partners. Her partners sit and wait for her to speak, when she eventually details the design parameters and their budget before they begin planning again	Self-Regulation	Complete
Maddie & Layla	5C: Maddie and Layla discuss their new design for blade shape, both citing reasons why they think they should make changes based on what the observed during the first testing session	Evaluation	Complete
Maddie & Layla	6C: Maddie asks Layla her opinion on how they should connect their blades to a dowel, explaining their options. Layla asks about the budget parameters and provides her opinion based on that information.	Interpretation & Inference	Complete
Maddie & Layla	7C: Maddie asks Layla if they should buy anything else. Layla responds with a question asking Maddie to remind her	Interpretation	Complete

	what they already have.		
Layla to Maddie	8C: Layla questions Maddie on the cost of their plan, questioning if she paid for a dowel yet. Maddie responds that she already factored it in	Interpretation	Complete
Maddie & Layla	9C: Maddie & Layla go back and forth reviewing their final redesign, checking in with each other on if they need any other supplies, and making sure that their plan has all required components (budget, labels, etc.)	Interpretation & Analysis	Complete

Every observed CTS during the redesign phase was coded as “complete,” which is a shift from the other two observed phases of the engineering design process. Insight for this finding can be gleaned from reviewing Figure 1, the Engineering Design Process. In engineering design units, the design process is often taught in a cyclical fashion [4]. In my classroom, we often work our way through the design process, and when we reach the redesign stage, I model going back through the process, starting with the design and plan stage a second time, followed by building, and testing. This second iteration through the design process is often less scaffolded than the first, as students have practiced these skills in the exact same setting at least one time already. It is likely that this repetition and familiarity with their group members and their project allows students to engage in deeper levels of CTS, which explains the greater number of “complete” skills during this phase.

For the first time, the critical thinking skill of “evaluation” was observed during the “Redesign” stage of the EDP. Putra et al. [4] outline *evaluation* within the EDP involving *assessing a claim* and using *evidence as argumentation*. They also frequently observed this skill during their version of the “Redesign” stage. After testing their designs and recording their data, students met with their group members with their original plans, data sheets, and new, blank planning sheets. Students were tasked with improving their design, choosing one design criteria to focus on (speed of blades/RPM or the cost of the blades) based on their findings from the testing stage. Therefore, it makes sense that we see students displaying complete CTS after formally testing designs and collecting data, as they have clear, concrete evidence to reference in their discourse on their redesigns. One example of this can be seen in a conversation between Annie and Sarah, summarized in Excerpt 6.

Excerpt 6: Sample of "Complete" Student Discourse in Redesign Stage (Group 1) (Instance 1C, *Evaluation*)

Student Performing	Brief Transcript	Timestamp
Annie to Sarah:	We should do two more blades and also make them sharper. Because I feel like if we do the square again, it won't like, cut the air and like, spin	2:58 - 3:06
Sarah to Annie:	"Okay"	3:07 - 3:08
Annie to Sarah:	*Begins writing on planning sheet* "So, (pauses, goes to get more markers)	3:09
Annie to Sarah	*Returns* "Okay, so we said we would do it the same as this one (referring to original plan) but with 5 [blades] "	3:52 - 3:58

Excerpt 6 demonstrates a "complete" instance of the *evaluation* CTS, as the students assess claims (more blades = more rotations per minute; blade shape impacts rotations) and make arguments from evidence. While students in this group didn't reference their data sheets for evidence (Appendices C and D), they did use their experiences (what they saw) during the testing stage to help inform their redesign.

Group 2 also demonstrates a prevalence of the skill of *evaluation* during the redesign stage of the design process. In fact, in Excerpt 7, we see Layla begin to engage in meaningful discourse with Maddie, asking specific questions for their redesign using their data from their first design as evidence.

Excerpt 7: Sample of "Complete" Student Discourse in Redesign Stage (Group 2) (Instance 5C, *Evaluation*)

Student Performing	Brief Transcript	Timestamp
Maddie to Layla	"Do you think we should do a popsicle shape?"	0:50 - 0:55
Layla	"Well... I..." *gets cut off by Maddie	0:55 - 0:56
Maddie to Layla	"I think we should do rounded because I feel like it worked well for other groups	0:56 - 1:02
Layla to Maddie	*Hesitates* "Can we make it like we did before? (references first blade and data sheet) because this one, like, works really good."	1:07 - 1:10

Megan was absent on this day of the design process, which likely impacted the dynamics of Group 2. It is difficult to know if this impacted Layla's renewed engagement with the project, although previous discourse transcripts did not demonstrate Megan dominating the conversation over Layla, so this is unlikely. Instead, it appears that after completing the stages of the EDP once before plus having concrete evidence to support her ideas, Layla finally appears to feel like she can meaningfully and confidently contribute to the group. In fact, Table 8 demonstrates five instances when Layla is engaged in a complete CTS.

In addition to *evaluation*, Group 2 demonstrated completion of the CTS of *interpretation.* Layla and Maddie frequently check in with each other and with their two iterations of planning sheets to clarify information and ensure that they are on the same page during moments of quiet work time, asking question such as *"Did we actually put hot glue on this part [of our plan?"]* - Layla to Maddie. This is a skill not observed in Group 1, who often worked in silence. These instances from Group 2 demonstrate the "complete"" performance of the CTS interpretation according to Putra et al, [4], which they state involves "clarifying meaning." Therefore, Maddie and Layla are both *performing* as engineers throughout this design stage, increasing their demonstration of an engineering identity.

Summary of Critical Thinking Skills in the Engineering Design Process

Different CTS were prevalent at each observed stage of the EDP, both "complete" and "incomplete." While the groups varied in the frequency of skills displayed, common trends emerged between the two groups, aligning with the findings from Putra et al. [4].

Each evaluated stage of the engineering design process involved the *performance* of multiple critical thinking skills, (both "complete" & "incomplete") but there one skill stood out at each stage of the design process: During the "planning" stage, students often performed the CTS of *self-regulation,* displaying a desire to assess their involvement in solving the problem, although it was often "incomplete." During the "Building" stage, students *analyzed* their designs that they planned with group members as they worked to make them a reality, and during the "Redesign" stage, students were more focused on using data to *evaluate* their designs, the performance skill that preoccupied this stage of the design process. This is the first time we observe this CTS, providing evidence regarding the importance of this stage of the EDP to foster an opportunity to perform as an engineer in this way.

The CTS o*f self-regulation* and *analysis* were present in all stages of the observed engineering design process. Despite being the most prevalent CTS across the EDP in this unit, both groups struggled with completion of the CTS of self-regulation without direct instructor mentoring. Self-regulating (which involves self-reflection and correcting) was a CTS found during the planning stage of Putra et al. [4] design process, which is when it was commonly observed as being an "incomplete" CTS during this study's EDP. As seen in Except 1, Layla struggled to orient herself to a specific role in the group, lacking assertion and the ability to self-reflect during the design and planning stage of the process - a CTS we also see her struggling to perform most CTS completely later in the EDP until she reaches the “Redesign” stage.

Group 1 struggled more with the completion of the CTS of *analysis* than Group 2G, indeed, group 2 exhibited the only “complete” CTS performance of *analysis* during the “building” stage of the design process. There are a variety of factors that could have contributed to this pattern, but after years of interacting with these students as their STEM instructor, I wonder how much of this pattern could be attributed to group size, peer familiarity, and personality traits, a possibility for future research.

During the final observed stage, “Redesign,” students from both groups demonstrated strong, “complete” performances of the CTS of *evaluating,* a finding consistent with the study from Putra et a. [4]. By this stage of the EDP, students have already “completed” each of the EDP steps once, and are asked to perform them again, using collected evidence. It is likely that due to this being their second time performing CTS in each of the shortened, modified steps of the EDP that are a part of the “Redesign” stage that students were able to complete these CTS more often than in previous stages. Furthermore, using collected data to inform the redesign process was modeled heavily in the classroom, a useful finding as I begin to prepare to teach the unit for a second time.

Implications

Various CTS were observed throughout the EDP, both “completely” and “incompletely.” *Evaluation* was the CTS “completed” most consistently by both groups, which leads me to reflect on my teaching practices during this stage of the EDP. Upon reflection, it is likely that the success of completing this CTS is due to two factors. First, students collected concrete evidence, providing them with the information they needed to defend their thinking. Second, it was explicitly modeled by the instructor on how to collect data and use it to formulate a new design, writing and speaking the process aloud as it was modeled during this stage of the EDP. This reinforces the importance of modeling and instructor scaffolding when teaching critical thinking skills within the engineering design process [20]. In fact, Brookfield [20] states in Chapter 5, *How Critical Thinking is Learned* in their book *Teaching for Critical Thinking: Tools and Techniques to Help Students Question Their Assumptions*, that the more personal and explicit a teacher can be in their modeling of critical thinking skills, providing discourse as they move through the process, the greater significance it has on a student's own thinking processes [20 p. 61].

Modeling various stages of the engineering design process and critical thinking skills, such as asking questions (CTS analyzing and interpreting), recording data, and making conclusions (CTS evaluating and interpreting) is an instructional strategy with tremendous potential to engage students in performing as engineers in structured settings. Furthermore, modeling the process of how to engage various critical thinking skills throughout the engineering design process may provide scaffolds for students of varying backgrounds and with different levels of experience in STEM problem-solving educational projects and units. This can provide opportunities for all students to perform as engineers. As I begin a new year of teaching, this is a crucial finding I will call upon to improve my instruction in order to better engage students from various backgrounds with different levels of experience, as I ask them to perform as engineers through the application of critical thinking skills.

The critical thinking skills of interpretation, analysis, evaluation, inference, and explanation are relatively concrete, so modeling as a strategy to help teach these skills is sufficient. The critical thinking skill of self-regulation however, requires more intrinsic's motivation and awareness of self along with one's preferred learning styles. This connects to the finding of the study indicating that self-regulation was most frequently performed as an "incomplete" CTS throughout the EDP. Putra et. al. [4] emphasized the importance of self-regulation within the EDP, as it provides students with multiple opportunities to improve (Putra et al., 2021). As I look ahead to a new school year, this research indicates the importance of teaching-time focused on the CTS of *self-regulation* with the aim of increasing the identity domain of *performance*. Since *self-regulation* requires students to self-correct, self-reflect, and assess their own *performance*, it is likely that research on the identity domain of *self-recognition* could provide some insight regarding how to increase student's sense of self within the field of engineering. This study found that self-regulation skills were at least attempted (if not "completed") across multiple stages of the EDP, making it clear that self-regulation is a crucial skill that students should be able to perform as engineers. While Putra et al. [4] also found self-regulation in multiple stages of the EDP, it was most frequently displayed in their study during the "Decide" (Redesign) stage of their process. Therefore, including the "redesign" stage of the engineering design process is an important step for educators to include when using engineering design projects in the classroom. Using this information, I seek to understand how to better embed opportunities to practice self-regulation during this stage of the EDP in my own practice to aid students in the development of their engineering identities through *performance.*

Conclusion

This study was designed to provide specific insight for elementary school STEM educators regarding how to support the development of student identities in STEM, specifically the domain of engineering. Using a well-renowned identity framework (Carlone & Johnson, 2007), a single aspect of identity (performance) was assessed through the application of critical thinking skills, as understood by the researchers Putra et al. [4]. As a result of the study, it was discovered that students perform certain CTS at specific steps of the EDP, such as analyzing and self-regulating during the planning and design stage of the design process. By identifying these instances of performances, it provides insight regarding what CTS students demonstrate the greatest competence in, and therefore, the greatest performance, ultimately contributing to a growing sense of their engineering identity. This information can then be used to improve and guide practice for educators as they usher students through the engineering design process.

Limitations and Future Research

For a STEM educator in an elementary school classroom without curriculum or a local, professional community to engage in discourse with, this study provided a helpful foundation for better understanding how hands-on engineering design projects help students develop and refine their performances as engineers through the application of critical thinking skills. However, it is not without limitations. First, this study took place in a single classroom with a single researcher who was also the classroom teacher. As noted in the positionality statement of the title page, this lack of separation from researcher and practitioner provides opportunities for direct growth, but also means that interactions with students are influenced by the relationship between the teacher and students, possibly influencing student responses and performances. Various scholars have noted the importance of relationships and the social aspects involved in identity development [21], [22]. The students in this study having a long - term (up to five years) relationship with the teacher/researcher may have impacted their STEM performances and identities long before this study took place. This provides an opportunity for future research on the implications of teacher-student and student-student relationships and identity formation within different learning contexts. Specific to this study, I wonder what connections (if any) would be found if I were able to access records to which students had been in classes together before, allowing for the formation of deeper relationships, would there be any correlation between group two's more complex and open discourse and the length of time the group members had known each other? It is likely that these factors influence their engineering identity to some degree, as Kim et al. [5] point out the connection between social identities and STEM identities.

An additional limitation for this research was the singular focus on CTS as an indicator of engineering performance [4]. A deeper study on student identities in engineering and STEM, specifically that for elementary school students, would benefit from a more robust review of literature and research conducted specifically for measuring performance in the engineering design process.

While a limitation of this study, the singular definition of CTS applied to the EDP to measure the domain of performance in student STEM identities provides an opportunity for further research, as well. An additional area for further research strays away from the emphasis on how to measure STEM identity, but would instead focus on other aspects of student identities (race, gender, class, etc.) and how these identities intersect with student engineering identities. It is naive to assume student engineering and STEM identities are developed in a silo, something which was evident even in the data collected for this study, as different personality types emerged from observations of students in group settings.

What is the connection between student performance/competence and student *self-recognition* in engineering activities? It appears that by participating in these activities, students developed a greater sense of *self-recognition,* a component of STEM identity, but it leads into another crucial and complex question of whether or not the actual performance as an engineer impacts a student's *recognition* of themselves (and *recognition* by others) as an engineer.

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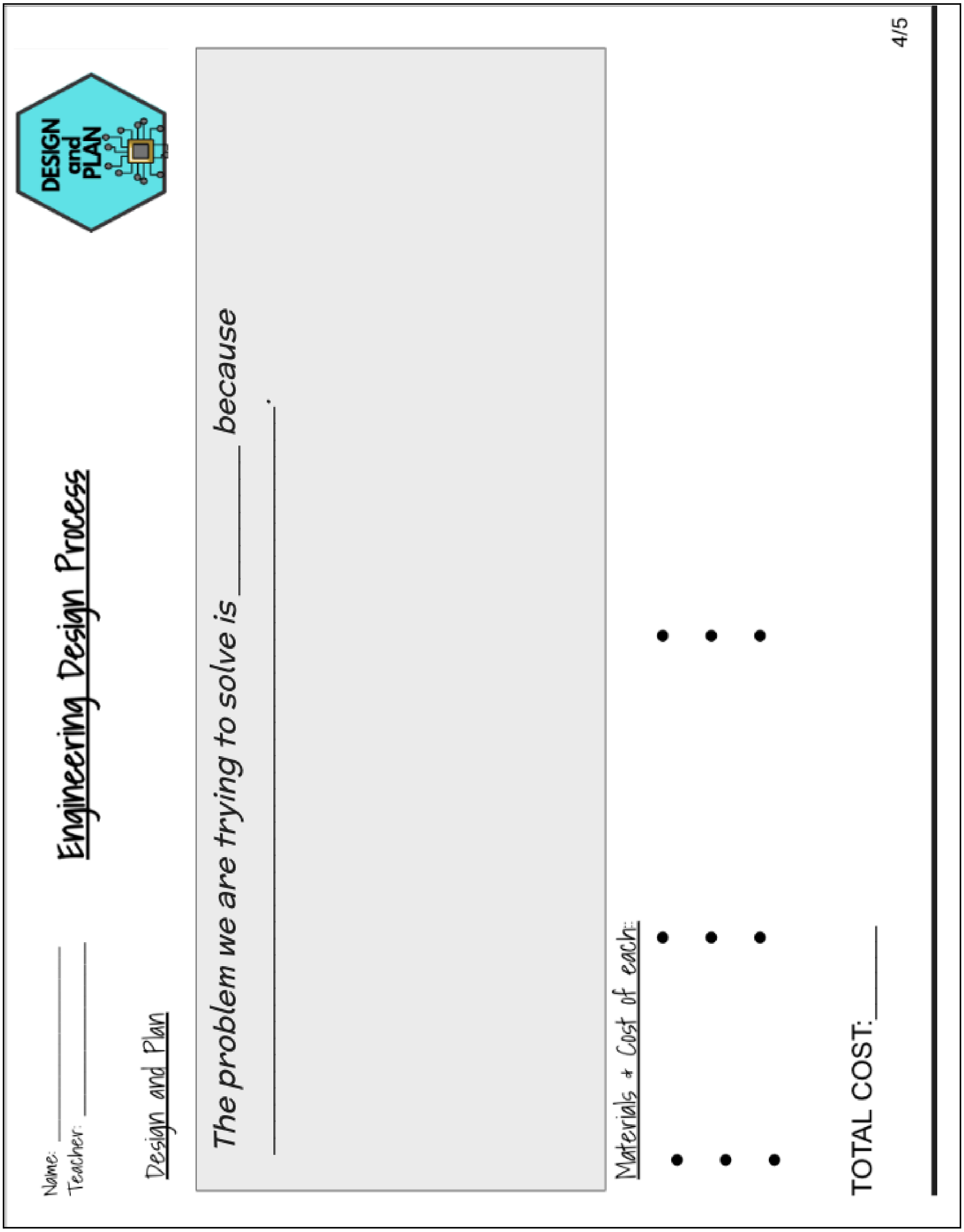
Appendix A *Planning Sheet*


Name: ____________

Teacher: ____________

Engineering Design Process

DESIGN and PLAN

Design and Plan

The problem we are trying to solve is ____________ because ____________.

Materials + Cost of each:

-
-
-

TOTAL COST: ________

4/5

Appendix B *Imagine & Explore*

Name: ____________

Teacher: ____________

Engineering Design Process:

Imagine and Explore - What we think we know

Show your thinking through modeling with a scientific sketch:

How does a wind turbine create energy?

Appendix C *Data Collection Sheet*

Name: ____________________

Teacher: __________________

Engineering Design Process

Number of Rotations in 30 Seconds	0 - 15 Rotations: Score: 1	16 - 30 Rotations Score: 2	< 30 Rotations Score: 3
Moved Solely By Wind Power (No push needed)	No Score: 0	Yes Score: 1	
			Total Score: ______ / 4

Design Notes:

# of blades: ______

Top 2 blade materials:________________

Blade spacing:______ (how many holes between each dowel on the hub)

Blade angle estimate: ______

**front facing fan directly = 0°*
**front facing perpendicular to fan = 90°*
**front facing between 0° & 90° = 45°*

An opportunity for improvement is

____

____

____

5

Appendix D *Reflection Form*

Name: ____________________

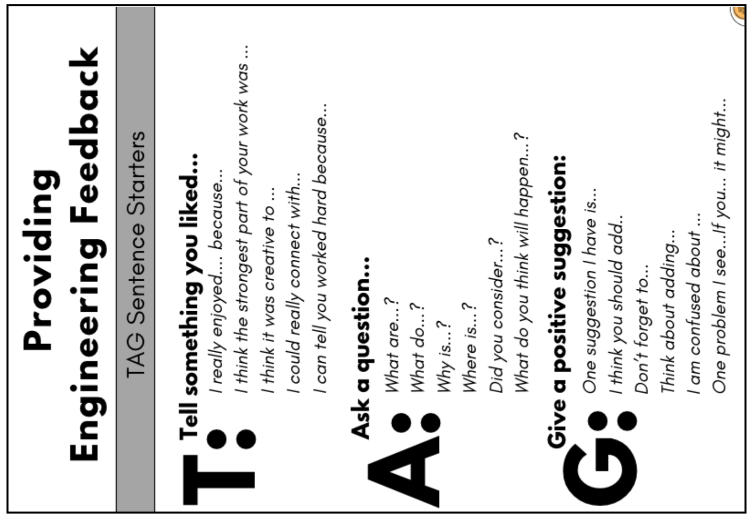
Teacher: ____________________

Engineering Design Process

1. The problem we were trying to solve was ____.
2. We tried to solve this problem by using these materials: ________________________.
3. The strongest part of my design was (*because*) ____
4. The weakest part of my design was (*because*) ____
5. An opportunity for improvement is ____

Appendix E *SWOT Analysis Handouts*

(In 4th grade, student groups at this school are able to choose one of the three handouts below to guide their redesign discussions)



Providing Engineering Feedback

TAG Sentence Starters

T: Tell something you liked...

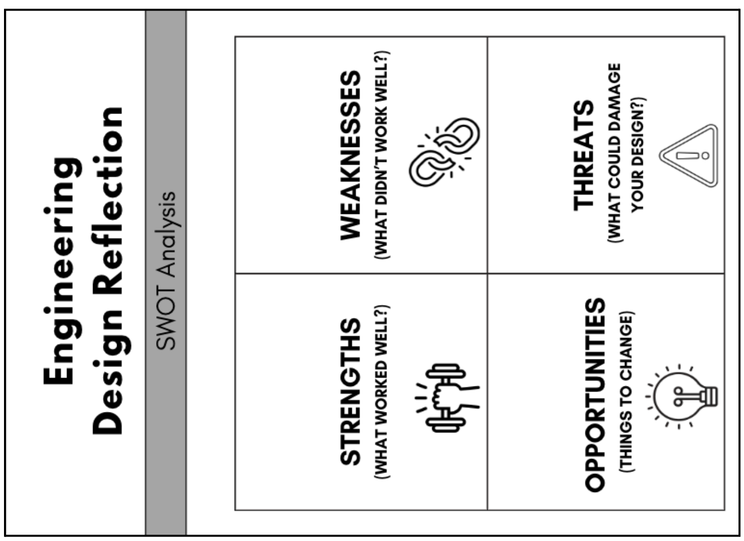
I really enjoyed.... because...
I think the strongest part of your work was ...
I think it was creative to ...
I could really connect with...
I can tell you worked hard because...

A: Ask a question...

What are...?
What do...?
Why is...?
Where is...?
Did you consider...?
What do you think will happen...?

G: Give a positive suggestion:

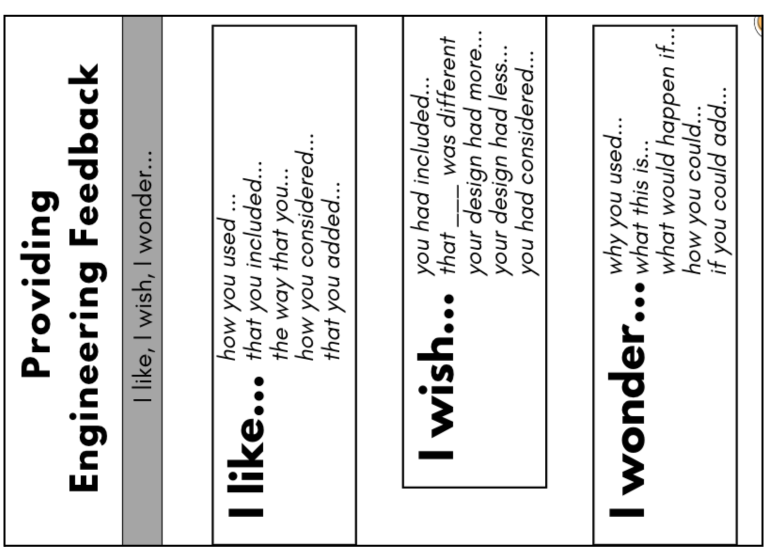
One suggestion I have is...
I think you should add..
Don't forget to...
Think about adding...
I am confused about ...
One problem I see...If you... it might...



Engineering Design Reflection

SWOT Analysis

STRENGTHS (WHAT WORKED WELL?)	**WEAKNESSES** (WHAT DIDN'T WORK WELL?)
OPPORTUNITIES (THINGS TO CHANGE)	**THREATS** (WHAT COULD DAMAGE YOUR DESIGN?)



Providing Engineering Feedback

I like, I wish, I wonder...

I like... *how you used ...*
that you included...
the way that you...
how you considered...
that you added...

I wish... *you had included...*
that ___ was different
your design had more...
your design had less...
you had considered...

I wonder... *why you used...*
what this is...
what would happen if...
how you could...
if you could add...