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Assessing Elementary Students' Engineering Design Thinking with an "Evaluate-And-Improve" Task (Fundamental)

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Assessing elementary students' engineering design thinking with an "evaluate-and-improve" task

Introduction

With the wide adoption of the Next Generation Science Standards [1], engineering has migrated to the elementary school classroom, often alongside existing science units. With funding from NSF's ITEST program and in collaboration with partner school districts, we developed integrated science and engineering curriculum units for elementary school students in Grades 3 through 5. In these units, students learn about a problem in their local community, then engage in related inquiry activities before designing and prototyping an engineering solution to the problem. As part of our iterative curriculum development process, we wanted to assess individual students' design thinking practices at multiple points in time. In this paper we describe the assessment tool we created to meet this need and share analysis of assessment results from one third grade classroom implementation in the final year of the project.

Prior work on engineering assessments for use in elementary classrooms has tended to focus on two sets of constructs: (1) students' knowledge about the nature of engineering and the engineering design process and (2) student attitudes towards engineering. For instance, the Draw An Engineer Test [2] was developed by Knight and Cunningham to capture students' conceptions of who can be an engineer and what engineers do. Similarly, another assessment designed by Cunningham and colleagues asked students to identify objects and activities as technology and engineering, respectively [3]. Some assessment tools test students' knowledge of the engineering design process [4], [5]. Additionally, researchers often administer engineering attitude surveys that gauge students' conceptions of themselves and their participation in engineering [4], [6], [7], [8], [9]. Outside of these research-oriented assessments, there exists a governmental effort to assess engineering thinking and design literacy at the fourth and eighth grade levels from the National Assessment of Educational Progress (NAEP). This Technology and Engineering Literacy (TEL) assessment includes scenario-based tasks that require students to propose and evaluate solutions to engineering design problems, but to date only its eighth-grade version has been administered and analyzed (in 2014 and 2018) [10].

Assessments like the Draw An Engineer Test and engineering attitude surveys accomplish the goals of the developers, namely, to determine students' perceptions of and knowledge about engineers and engineering. While these are important goals, we needed an assessment that more closely aligned with our curriculum goal of fostering students' sophisticated enactment of engineering practices. Specifically, our aim was to provide teachers with a usable classroom tool that would provide information about how students think about engineering designs. Thus, we designed our own assessment, an "evaluate-and-improve" task that asks students to evaluate an existing design, propose changes to a design, and justify those changes with reasoning. These goals are consistent with a subset of the NGSS and other frameworks for elementary engineering education [1], [11], [12]. They specifically align with the NGSS practices of identifying problems, designing solutions, and engaging in argument from evidence. We refer to this collection of practices in this work as students' *engineering design thinking*.

Over the course of the project, we revised and administered this assessment several times. This study presents data from the administration of the final version of the assessment before and after one of the integrated science and engineering curriculum units we developed as part of this project. We coded student responses to the assessment task and examined frequency of codes to address our research question: *To what extent does a written evaluate-and-improve task reveal a range of engineering design thinking across different third-grade students and capture changes in their engineering design thinking after an engineering learning experience?* In the findings section, we present a characterization of the changes and justifications that students proposed, followed by preliminary conclusions about the potential influence of the curriculum and collaboration on student responses.

Methods

Participants and Context

Data for this paper comes from the ConnecTions in the Making project (NSF ITEST #1657218). As part of this project, we developed six distinct curriculum units for grades 3-5, implemented in 21 classrooms over 3 years. This study focuses on one implementation in a third-grade classroom during the final year of the project. This third-grade classroom comes from a racially and socio-economically diverse elementary school in the suburbs of the Northeastern United States. Of the 21 students in the class, only data from the 14 assenting students are included in this analysis.

Over the course of 10, hour-long classroom sessions, the class participated in our Accessible Playgrounds unit, centered around the science of unbalanced forces and magnetism and the engineering of accessible playground design. The classroom teacher divided the class into five different groups, each consisting of three to four students. The groups engaged in various inquiry and design activities involving the designing, modeling, and testing of a piece of accessible playground equipment that could be used by children with and without physical disabilities. Students took the pre-assessment before the unit launch, spent five days completing inquiry activities, designed and built their playground models for the following five days, and then took the post-assessment after sharing their completed projects on the tenth and final day.

Assessment Task and Administration

Students completed the evaluate-and-improve task as a paper-and-pencil assessment before and after the unit. On the paper handout (included in full in the Appendix), students read about and saw an image of an unbalanced, lopsided cart transporting classroom plants (Figure 1). The plant cart was made of one large wooden board, three wheels, and a rope handle. The rope was tied around the board behind the front wheel. When the rope was pulled, it got stuck in the front wheel and the cart would not move in the correct direction. The plants then slid off and fell to the ground. Students were provided with a picture of this scenario and asked to circle the part(s) of the cart that caused the problems. They were then asked to propose changes to fix each issue and support those proposed changes with a brief explanation.

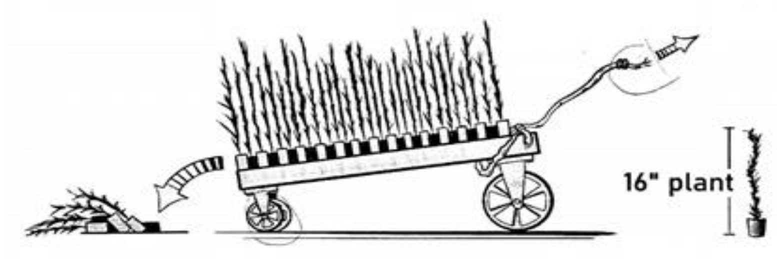


Figure 1. Example of the assessment task image, with student markings showing problems they identified with the system.

Data Analysis

We collected the responses and began our data analysis by transcribing and organizing students' pre- and post- assessments. Our analysis focused on two key components of the evaluate-and-improve task: (1) the proposed changes to the cart system and (2) the students' justifications for each proposed change. First, two researchers (the first two authors) independently reviewed each students' sketch, list of proposed changes, and justifications for the changes, and made a list of unique proposals. We compared these lists to generate a set of codes for proposed changes. We then graphed the frequency at which each proposed change occurred in both the pre- and post-assessments (See Findings, Figure 2).

In the analysis of student justifications for changes made to the cart, we again independently reviewed student responses and used open coding to note themes. We compared and consolidated these initial themes to create a codebook for students' design change justifications (Table 1). We then revisited the data corpus and assigned codes to each pre- and post-assessment response. To establish interrater reliability, we also asked two other members of our lab group to independently code all student responses based on the codebook we formulated. Initial agreement was 79% for the pre-assessment responses (among three independent coders) and 78% for the post-assessment responses. We then met as a group and compared our codes. When a discrepancy existed, we discussed the student response until we agreed on which code(s) to assign to it. These discussions highlighted codes that were unclear or under-defined, so we revised the definitions to be more straight-forward and grounded in the written explanations proposed by students. The revised codebook includes seven distinct justifications, a definition for each, and a student example, as shown in Table 1. Once we had reached consensus on coding, we then graphed the total number of justifications provided by each student, the frequency at which the justifications occurred in both the pre- and post- assessments, and the student-group trends in justifications.

One limitation of this approach to assessing students' engineering design thinking is that the students' written responses may not have captured all of their ideas or approaches to identifying problems and designing solutions. We acknowledge that they may have had other ideas during classroom discussions that were not analyzed in this particular study.

Table 1. Revised codebook of student justifications.

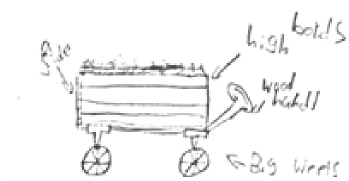
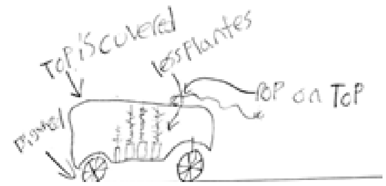
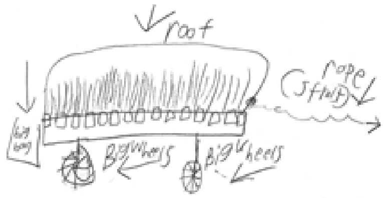
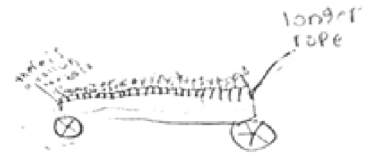
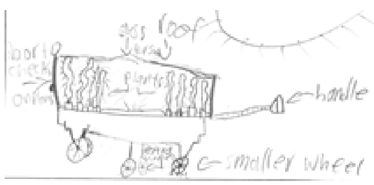
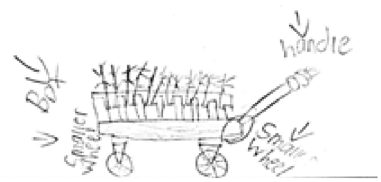
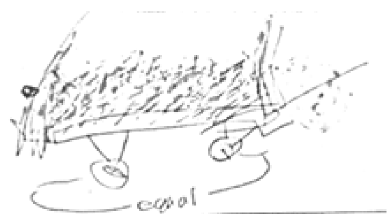
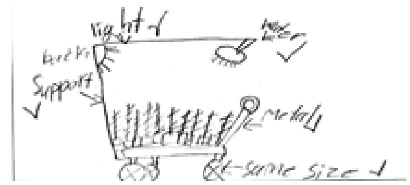
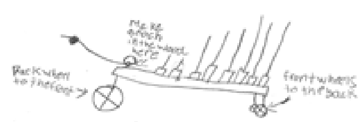
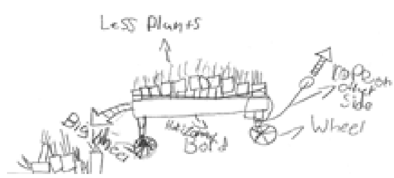
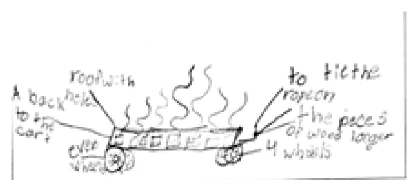
Code	Definition	Student Example
FALL	Proposed change would stop the plants from falling off the cart.	“Because I think if they put big wheel at the back then plants [won’t] fall”
STUCK	Proposed change relates to the rope getting stuck in the cart.	"The [metal circle] that is were you [tie] the rope so it [doesn’t] get in the way of the [wheel]”
USE	Proposed change relates to human interaction with the cart and ease of use.	"I added a long rope so the student does not get hit by the wheel."
ALIVE	Proposed change would meet the needs of the plants to keep them alive.	"I suggest sprinklers so the plants can grow and I suggest to cut 3 holes so the sun can shine on the plants"
BALANCE	Proposed change would make the cart level/balanced.	"Even wheels so it is not [leaning] to one side or the other. 4 wheels so the cart [balances]."
MOVE	Proposed change would affect the movement of the cart.	"I suggested to put the rope on the side where the two wheels are because I think it will go faster"
WEIGHT	Proposed change would change the weight of the cart.	"Less plants because less plant = less [weight]"

Findings

To address our research question *To what extent does a written evaluate-and-improve task reveal a range of engineering design thinking across different third-grade students and capture changes in their engineering design thinking after an engineering learning experience?* we built figures that modeled the scope of student responses.

Table 2 shows the various changes suggested students. Across the pre- and post- assessments completed by 14 students, 14 unique features were proposed. Students were rich and creative in their solutions, often going beyond the scope of the problem. Notably, one student proposed a sail to help the cart move faster, another drew animals to pull the cart, and others suggested light and sprinklers to keep the plants alive.

Table 2. Student examples of proposed features to change in the cart.

Proposed change	**Student Example**	**Proposed change**	**Student Example**
Side or back reinforcement		Move Rope	
Roof		Lengthen Rope	
Extra Wheel		Change or Strengthen Rope	
Same Sized Wheels		Plant Life	
Reverse Wheels		Less Plants	
Animals		Sail	
Strengthen Cart		Lengthen Cart	

We were interested in how many students proposed each of the changes identified in Table 2. To illustrate this, Figure 2 shows the frequency of each change suggested by the students in the pre- and post-assessments. Both before and after the unit, the additions of side or back reinforcements to the cart and equal sized wheels were the most popular changes proposed. Ideas like the introduction of animals to pull the cart, a sail, strengthening the cart, or lengthening the cart, were only suggested by one student. Two ideas, reversing the wheels so that two were in the front of the cart and one in the back and the use of animals, were proposed in the pre-unit assessment but were abandoned in the post-unit assessment. Additionally, the post-unit assessment brought about a new change, strengthening the cart, that was not suggested in the pre-assessment.

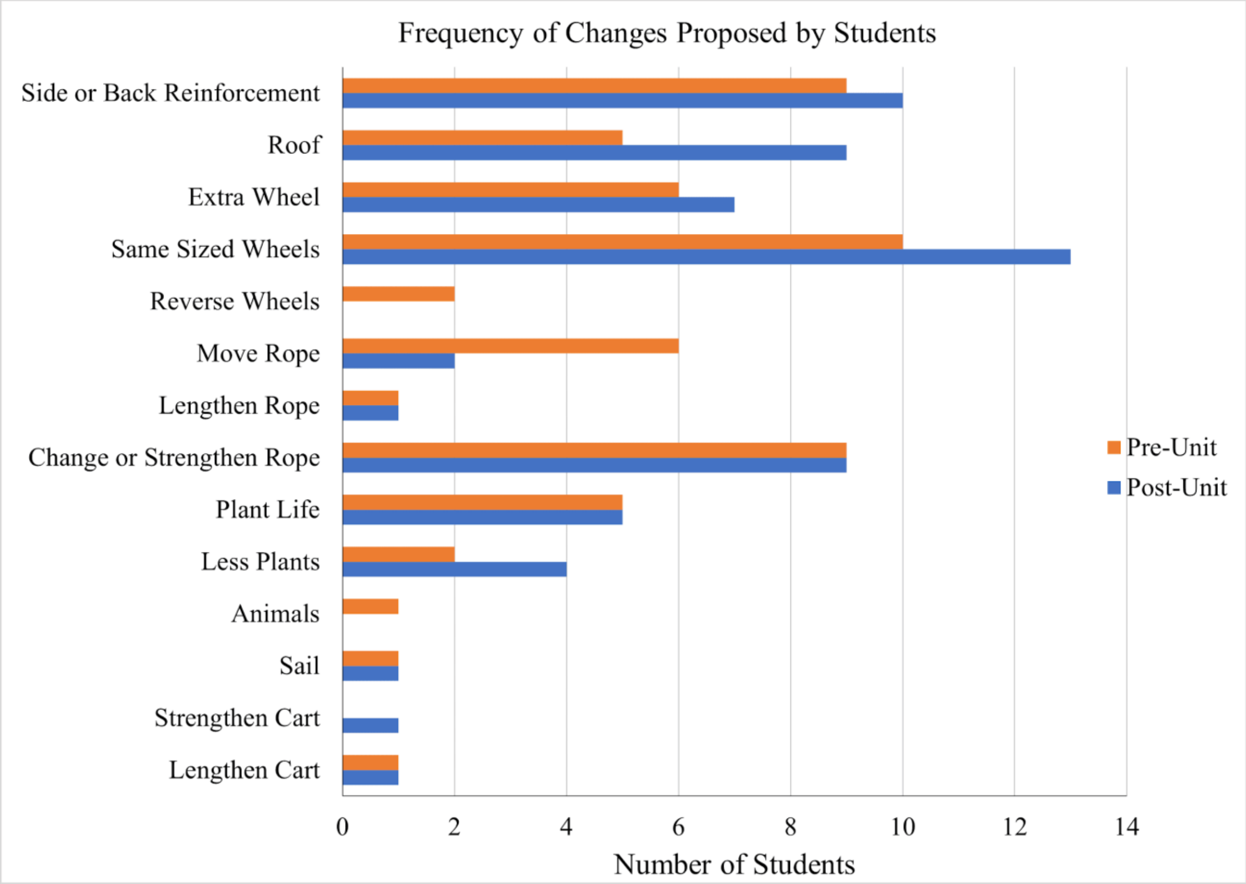


Figure 2. Frequency of proposed changes by students in the pre- and post- unit assessments.

Students were asked to provide justifications to support each change they made to the cart. Figure 3 (left) shows the number of reasons given per student response on the pre-assessment. Four students (28%) did not include justifications in their pre-unit explanations. These students probably had justifications for their suggested changes, but they did not write them down so they could not be counted. However, in the post-unit assessment, these four students all included at least two justifications in their explanations. Figure 3 (right) shows that in the post-unit assessment, all 14 students had at least one reason for a change in their explanations and one student provided four justifications for their changes.

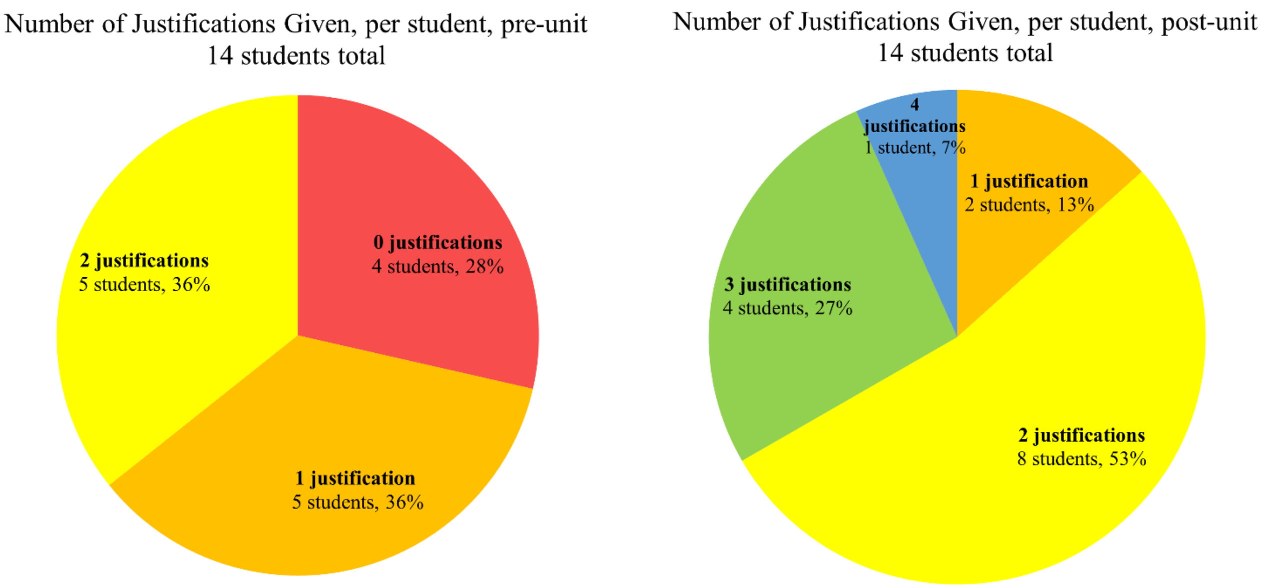


Figure 3. Number of justifications students provided to support the changes made to the cart pre-unit (left) and post-unit (right).

To support the changes they proposed, students used a combination of seven distinct justifications. The frequency at which these justifications occurred in the pre- and post-unit assessments is modeled in Figure 4. In the pre-unit assessment, students provided a combination of four justifications. In the post-unit assessment, students incorporated seven justifications into their explanations, three of which were not seen at all in the pre-unit assessment. Students' explanations included more justifications overall after the unit compared to before the unit.

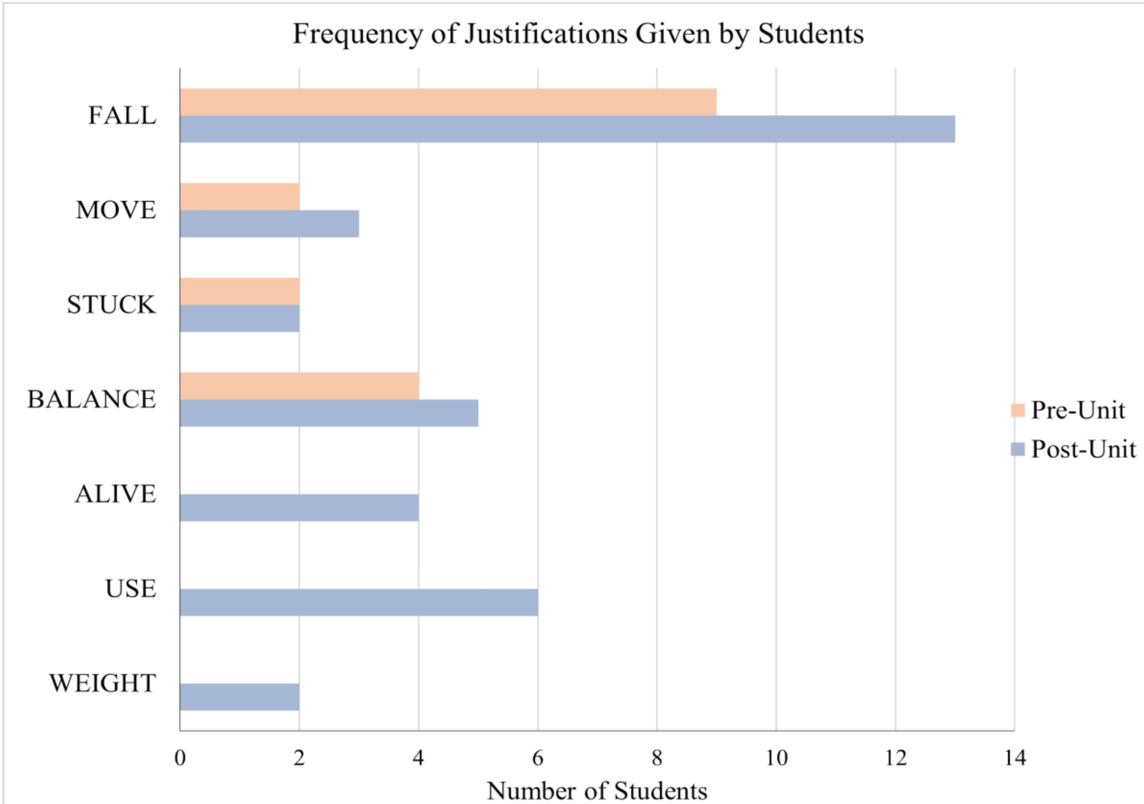


Figure 4. Frequency of justifications given by students in the pre- and post-unit assessments.

Figures 5 and 6 model student reasons provided in the pre- and post-unit assessments, organized by student group. Even though students completed the assessments individually, the figures reveal that group collaboration during the unit may have been associated with the students' understanding of the evaluate-and-improve task. Figure 5 shows the pre-unit justifications provided by students, before the groups were formed, and reveals no apparent trend by student group. However, it is notable that all members of Group 3 provided the "FALL" justification. Figure 6, the model of student justifications provided per group in the post-unit assessment, reveals a possible influence from group collaboration on the post-assessment. For example, in Group 1, all members supported their changes with the "FALL" code and two members used the "ALIVE" code. In Group 2, two members used the "FALL" code and a different combination of two members provided the "USE" reasoning. In Group 4, all of the members' responses included the "FALL" and "BALANCE" codes.

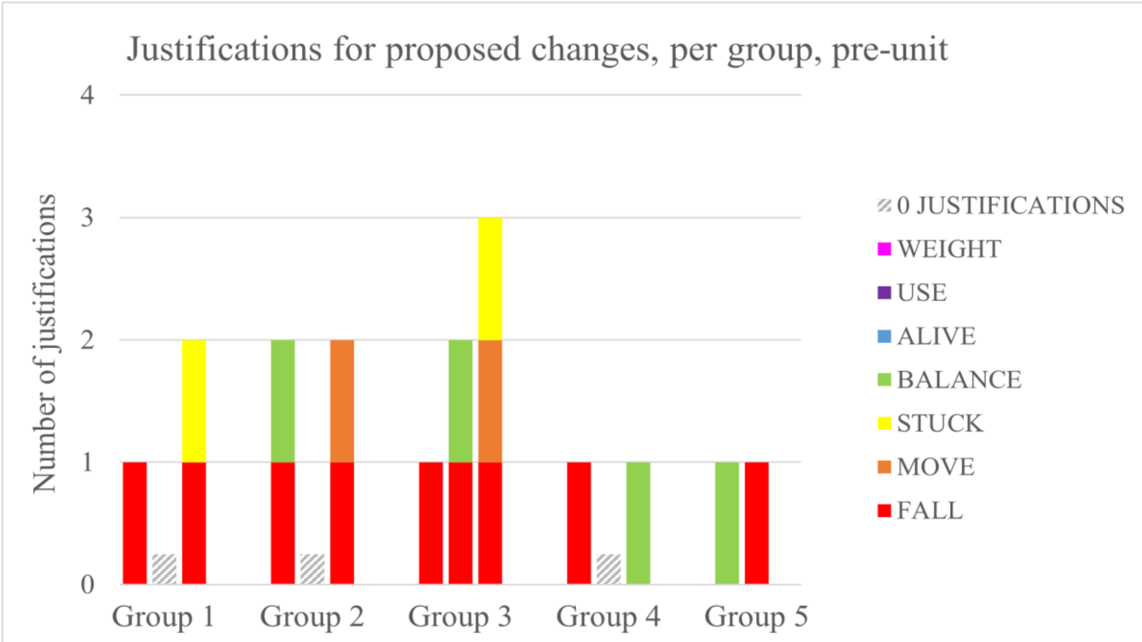


Figure 5. Student justifications provided per group in the pre-unit assessment.

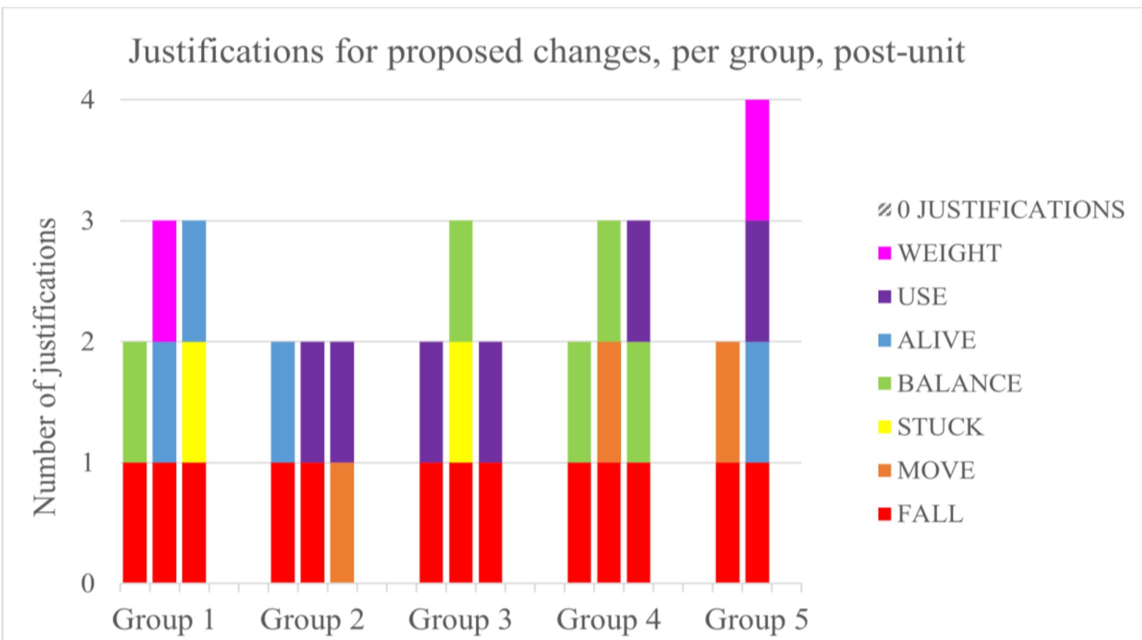


Figure 6. Student justifications provided per group in the post-unit assessment.

Discussion

In our analysis of the assessment, we focused on *the extent that the written evaluate-and-improve task reveals a range of engineering design thinking across different third grade students* and how it could *capture changes in their engineering design thinking after an engineering learning experience*. We found that in their evaluate-and-improve task, the 14 students proposed a total of 14 distinct changes to make to the lopsided plant cart. We were impressed by this number because although the assessment is an open-ended task where students are prompted to generate their own ideas, its design problem (the lopsided plant cart) is not a scenario the students studied firsthand in the classroom. Therefore, there was a risk that it might not engage students' interest and cognition and therefore not serve its purpose of eliciting evidence of students' engineering design practices. To the contrary, students proposed numerous and divergent changes to the plant cart and articulated a range of reasonable justifications for those changes. Thus, in this study, we showed that a standalone paper-and-pencil task can capture evidence of engineering design practices by individual third graders. Previous reports of design practices by students this young have required laborious collection and analysis of classroom video data (e.g., [13], [14]) or of interviews with think-aloud protocols [15]. Of course, video- and interview-based case studies of student participation in engineering design learning experiences are crucially important for building theory and improving curriculum and pedagogy. However, it is also important for the engineering education community to have assessment tools that are feasible for implementation across an entire class in a single session. The evaluate-and-improve tool that we have developed was easily implemented by the classroom teacher and richly generative of student engineering design practices. It offers an alternative to existing elementary engineering assessments that focus on knowledge of engineering and the engineering design process; it prompted students to engage in reasoning about a specific design problem and solution.

In explaining their reasoning behind each change proposed to the plant cart, students provided 7 distinct justifications. Their reasoning was sorted into the codes "FALL", "WEIGHT", "ALIVE", "USE", "BALANCE", "WEIGHT", and "STUCK". Similar to the changes they proposed, these justifications exemplify student creativity. "FALL" was the most common justification, meaning that student reasoning related to preventing the cart from falling. This was a more obvious answer because it is highlighted in the question, but we were impressed by students providing reasoning that went beyond the scope of the problem and interpreting the assessment in their own way. Students provided more justifications of their ideas in the post-assessment with two ideas only appearing after the unit. This suggests that the students' engineering design thinking practices or their capacity to articulate their engineering design thinking may have grown stronger over the course of the curriculum unit.

The assessment results also suggest that the particular foci of students' engineering design thinking may be related to particular curriculum activities or to their particular small group experience. Some students within the same group had similar reasonings in their post-assessment that were not seen in the pre-assessment, before the formation of small groups. Additionally, the unit itself may have influenced students' engineering design thinking, as highlighted by three additional types of justifications that appeared in the post-assessment. The class curriculum focused on accessibility, asking students to think about particular users, their safety, and how they uniquely interact with playground equipment. The unit also included several inquiry activities that investigated unbalanced and balanced forces and motion. In the post-assessments, we saw the advent of three new justifications: "ALIVE," regarding the living nature of the plants; "WEIGHT," regarding changing the weight of the cart; and "USE," regarding the human interaction with the cart. Each of these relates to the safety of the plants and the human interaction with the cart. This indicates that responses in the post-assessment may have been inspired by the engineering curriculum.

Although the evaluate-and-improve assessment captured evidence of student engineering design thinking and across-team differences in reasoning in this study, it may be limited by the fact that it is a writing-heavy task administered in English. This would make completion difficult for students who are emerging writers or emerging bilinguals. In the future, we could adapt the assessment by using simpler language and more pictures, by administering it orally, or by translating it into students' home languages.

Our exploratory study of this evaluate-and-improve task suggests that it gives third-grade students an opportunity to demonstrate their ability to scope problems, propose design iterations, and justify those changes. Students were creative in their responses and engineering design thinking, often going beyond the scope of the initial problem. In addition, we saw the potential influence of the engineering curriculum and small group collaboration on student responses.

Acknowledgements

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Appendix: Full Assessment Task

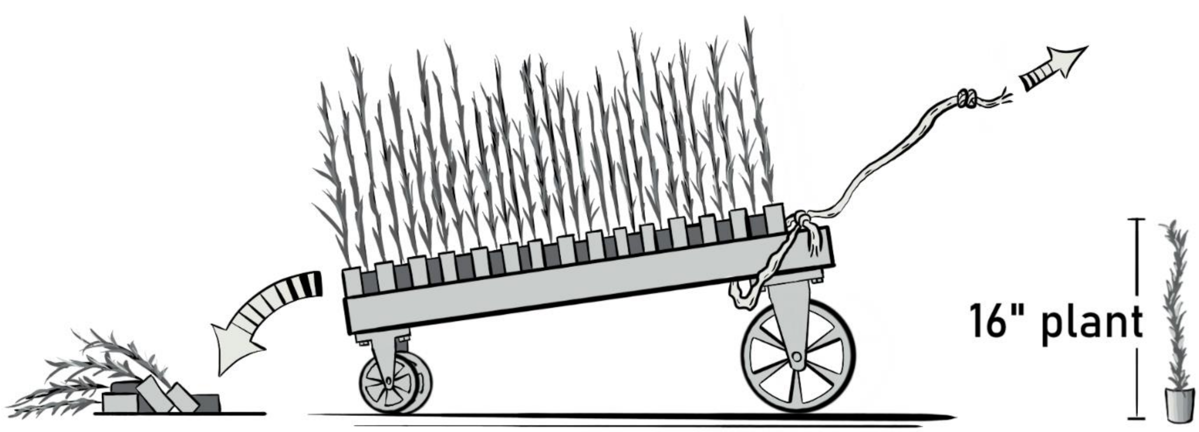
Name ____ Date ________________

ConnecTions Project Pre/Post Survey

A picture of a cart carrying 12" bean plants is shown below. This cart was designed by some students to help their teacher move growing bean plants from their classroom to another. The students made the cart out of one large wooden board, three wheels, and some rope. The rope was tied around the board behind the front wheel. When the students put 50 plants on the cart and pulled the rope, the rope got stuck in the front wheel and the cart wouldn't move in the correct direction. Then the plants slid off the cart and fell onto the floor.

Here is a picture of the cart and what happened to the plants. They slid onto the floor!

Circle the parts of this cart that you think caused this problem:



Draw and label your changes for improving the cart:

List your changes	Why do you suggest each change?