122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society
Paper ID #13735

# Urban elementary school students' reflective decision-making during formal engineering learning experiences (Fundamental)

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## Abstract

A key component of engineering design cognition is reflective decision-making that takes into account information about design options. As the *Next Generation Science Standards* ask K-12 students to learn the practices of engineering design, those students need opportunities for reflective decision-making. The purpose of our work is to shed light on the ways in which students exhibit reflective decision-making during engineering design experiences in culturally and linguistically diverse urban school settings. In this qualitative descriptive research study, we investigated the question, *what does reflective decision-making look like among urban elementary school students participating in a formal engineering design curriculum?* We video recorded seven *Engineering is Elementary* design challenges and collected student written work in four different urban classrooms, and we viewed and discussed video episodes and student artifacts at teacher/researcher meetings. Using qualitative descriptive methods, we analyzed the classroom data to systematically confirm or disconfirm hypotheses about the elements of urban elementary students' reflective decision-making in engineering. We found strong and wide-ranging evidence for six components of students' reflective decision-making. Based on this evidence, we argue that reflective decision-making does take place during engineering design experiences in culturally and linguistically diverse urban classrooms, and we present two student group case studies to support that argument. We discuss implications of this work for elementary engineering instructional design, pedagogy, and educational research.


## Introduction

In its *Framework for K-12 Science Education,* the National Research Council writes, "Engineers, too, make decisions based on evidence that a given design will work; they rarely rely on trial and error" (NRC, 2012, p. 62). For engineers to plan feasible solutions and revise solutions they have already tested, they need to engage in *reflective decision-making* that takes into account information about design options. This intentional, informed reasoning about what to do next is a key component of engineering design cognition (for a review, see Crismond & Adams, 2012).

The *Next Generation Science Standards* ask K-12 students to learn the practices of engineering design (NRC, 2013), the backbone of which is collaborative and reflective decision-making. Therefore K-12 students need opportunities to carry out reflective decision-making, and educating "the reflective practitioner" (Schön, 1987) could be considered the implicit aim of pre-college engineering education. In our research program, we explore the nature of reflective decision-making in elementary school engineering design. We examine students' collaborative engineering discourse for evidence of reflective decision-making. In particular, we look for reflective decision-making practices while students participate in planning (i.e., developing possible solutions) and redesign (i.e., iteration) phases of engineering design during classroom implementation of units from the widely used and National Science Foundation-supported

*Engineering Is Elementary (EiE)* curriculum program (Museum of Science Boston, 2015).

In this qualitative descriptive research study, we investigated the research question, *what does reflective decision-making look like among urban elementary school students participating in a formal engineering design curriculum?*

**Theoretical Framework**

This study is grounded in a "resources perspective" (Hammer & Elby, 2003) for recognizing the intellectual and linguistic practices that children from urban communities bring to engineering design processes. A variety of challenges associated with urban schools have often led to the portrayal of students in ways that are consistent with a "deficit perspective" on performance (Varelas, Kane, & Wylie, 2011). In contrast, educators and researchers who adhere to a "resources perspective" (e.g., Bang & Medin, 2010; Emdin, 2011) argue that numerous characteristics of urban communities, schools, and students can be interpreted as resources rather than challenges or deficits.

We synthesize two sources of information to propose an *a priori* definition of reflective decision-making in elementary school engineering: first, the research literature on engineering design cognition literature, and second, a content analysis of the *EiE* curriculum materials.

Prior studies of college and professional engineers highlight the role of reflection and language in engineering design (Atman, Kilgore, & McKenna, 2008; Aurigemma, Chandrasekharan, Nersessian, & Newstetter, 2013; Kittleson & Southerland, 2004). Engineers work in a range of linguistic modes in which oral, written, and schematic language interacts frequently with the physical manipulation of materials and with symbolic representations (Aurigemma et al., 2013). Engineering designers share common design discourse (Atman, Kilgore, & McKenna, 2008), but achieving fluency in this discourse and being able to leverage it for group knowledge construction requires both time and experience with appropriately challenging design problems (Kittleson & Southerland, 2004).

A related body of work describes the evolution of design approaches as engineers shift from novice to expert practice (Atman, Adams, Mosborg, et al., 2007; Cardella, Atman, Turns, & Adams, 2008; Crismond & Adams, 2012; Cross, 2004). As engineers become more expert designers, they rely more heavily on reflective decision-making. For example, in one study, recently graduated engineers utilized a systematic trial-and-error approach where they implemented and evaluated each design idea through many iterations. By contrast, their experienced colleagues evaluated tentative design ideas before implementing them, thus engaging early in reflective decision-making and spending their time implementing only potentially fruitful ideas (Ahmed, Wallace, & Blessing, 2003). A case study of three exceptional engineering designers (as they thought out loud while designing a bicycle carrier, sewing machine, and racing car) revealed three reflective orientations that they all shared (Cross, 2003). They all reflected at length on the problem space and framed the problem from the perspective of their own personal experiences, they all articulated connections to physical principles throughout their design process, and they all described a productive tension between their own high-level problem goals and the clients' requirements for an acceptable solution. Crismond and Adams'

(2012) meta-analysis of studies of informed designers confirmed these case study findings. Informed designers "design with an abundance of ideas" and use techniques such as brainstorming and divergent thinking to avoid favoring any single solution at first (Crismond & Adams, 2012; Shah & Vargas-Hernandez, 2003). They are reflective about the benefits and trade-offs or potential design decisions, whereas beginning designers tend to ignore those trade-offs. Informed designers are also explicit about the design strategies they are using, rather than following tacit procedures (Atman et al., 2007; Crismond & Adams, 2012).

Whether novice or expert or on the continuum in between, all engineering designers' practice involves the creation of representations of their work (Dym, 1994), which assist them in analyzing and testing the work they are producing (Bucciarelli, 1994). They reflect on these representations as they check that an initial conceptual design satisfies all the requirements of the problem statement, for example. They also make reflective decisions when developing and implementing complex mathematical models of their designs. This emphasis on analysis and testing leads to iterative redesign as another universal feature of engineering (Petroski, 1996). One fruitful approach to redesign is "diagnostic troubleshooting" (Crismond & Adams, 2012), when engineers focus their attention on problematic areas of a design solution as they view performance tests of prototypes.

From idea generation and evaluation to troubleshooting and redesign, engineering design practitioners engage in reflective decision-making to determine evidence-based next steps.

With the goal of introducing elementary students to the practices of engineering design, the *Engineering Is Elementary* curriculum (Museum of Science Boston, 2015) creates opportunities to engage in reflective decision-making. A content analysis of the components of an *EiE* curriculum unit reveals when these opportunities occur. The *Engineering Is Elementary* curriculum units all follow a sequence of four lessons. In the first lesson, students read a story about a child using engineering to solve a problem. This problem becomes the basis for the design challenge that the students will solve later in the unit, and the story introduces five phases of engineering in child-friendly language: "Ask, Imagine, Plan, Create, Improve." The second lesson of every *EiE* unit builds students' knowledge of a particular field of engineering, such as electrical engineering in the circuit design unit *An Alarming Idea: Designing Alarm Circuits*, or environmental engineering in the water filter design unit *Water, Water Everywhere: Designing Water Filters*. The third and fourth lessons turn the students' attention back to the design challenge, which is derived from the problem that the character in the story solved. In the third lesson, students ask questions about the design challenge and carry out a science investigation of the materials they will be using to solve it. In the fourth lesson of the unit, students are expected to apply results from the investigation to plan and prototype their own solution to the unit's design challenge.

The first and second lessons of any *EiE* unit can be considered learning experiences that build students' knowledge *about* engineering and the work of engineers. The third lesson helps students to engage in scientific inquiry, data collection, and analysis to learn more about the properties of materials. The fourth lesson is the one where students have the chance to *do* engineering. Therefore, we focus on the fourth lesson and ask, where does the fourth lesson of each *EiE* unit create space for the "beginnings" (Watkins, Spencer, & Hammer, 2014) of the reflective decision-making that college and professional engineers have been found to do (see Table 1)?

Lesson 4 of an *EiE* unit begins with the "Imagine" phase by asking students to work independently to sketch multiple possible solutions to the design problem. Typically the instructional materials for Lesson 4 include an "Imagine" handout with four boxes in which students can draw their design sketches. The next step of Lesson 4 is "Plan," in which students are asked to work with their group to determine a single design proposal to prototype. They are supported by a "Plan" handout that gives space for a single design sketch and materials list. As they collaboratively choose the best possible solution, they are encouraged to take into account the data they collected in Lesson 3.

These "Imagine" and "Plan" learning tasks afford students the opportunity to engage in elements of reflective decision-making common to engineers as they conduct initial planning of design solutions. Specifically, they carve out space for students to

1. *Articulate and review more than one idea about how to solve a design problem.*
2. *Reflect on pros/cons of options according to the criteria and constraints of the problem, mathematical and scientific principles, and critique by other children and adults.*
3. *Intentionally select a potential solution to pursue.*

After collaborating on a design plan, each student group constructs a prototype and records information about how it performs on specified tests. The "Create" handout typically poses questions about test results and often provides a data table template to support documentation of prototype performance. The final part of Lesson 4 is "Improve," where students are asked to use information about prototype performance to improve their design, ideally with the goal of achieving better test results. The "Improve" handout gives space for students to write and draw about their proposed improvements. These "Create" and "Improve" learning tasks within Lesson 4 also afford opportunities for reflective decision-making similar to that practiced by professional engineers. In particular, opportunities exist for students to

4. *Re-tell the performance of a possible solution.*
5. *Analyze possible solution(s) according to several types of evidence, including results of physical tests, data from scientific investigations, information from external sources, and critique by other children or adults.*
6. *Purposefully choose how to move forward to improve the proposed solution.*

Table 1. Alignment of proposed definition of reflective decision-making in engineering with supporting research and elementary engineering curriculum learning tasks

| Elements of reflective decision-making | How engineering design practitioners exhibit the element | Related learning tasks in the *EiE* curriculum |
|---|---|---|
| *During initial planning* | | |
| Articulate and review more than one idea about how to solve a problem | Generate multiple options before developing any one in detail (Atman et al., 2007) | Create more than one design sketch to show more than possible solution ("Imagine" handout) |
| | Idea fluency (Crismond & Adams, 2012) | |

| | | |
|---|---|---|
| Reflect on pros/cons of options according to the criteria and constraints of the problem, mathematical and scientific principles, and critique by other children and adults | Refer to physics principles throughout designing process (Cross, 2003)<br><br>Construct and analyze models to assist with idea evaluation (Aurigemma et al.; Dym, 2004)<br><br>Balance benefits and trade-offs (Crismond & Adams, 2012) | Use data generated by the investigation of material properties in Lesson 3 |
| Intentionally select a potential solution to pursue | Generate designer's own goals along with client's (Cross, 2003)<br><br>Move to detailed design after feasibility analysis (Atman et al., 2007) | Collaborate with teammates to determine only one proposal to pursue at first ("Plan" handout) |
| *During redesign* | | |
| Re-tell the performance of a possible solution | Conduct tests or experiments and represent results (Bucciarelli, 1994; Kittleson et al., 2014) | Carry out specific tests of prototype ("Create" handout) |
| Analyze possible solution(s) according to several types of evidence, including results of physical tests, data from scientific investigations, information from external sources, and critique by other children or adults | Focus on problematic areas of prototypes through "diagnostic troubleshooting" (Crismond & Adams, 2012) | Record test results on specific data tables or by answering specific prompts ("Create" handout)<br><br>Revisit data from Lesson 3 about properties of materials |
| Purposefully choose how to move forward to improve the proposed solution | Iterate by making small gradual changes both to understanding of the problem and to the proposed final solution (Adams et al., 2003; Petroski, 1996) | Write and draw about ways to make the design better ("Improve" handout) |

## Method

We used a qualitative descriptive research approach (Merriam, 1998) to investigate the extent to which students in diverse urban elementary classrooms engage in reflective decision-making during a formal engineering curriculum. Drawing on methods of naturalistic inquiry (Lincoln & Guba, 1985) and content analysis (Miles & Huberman, 1994), we used students' oral and written language as qualitative data and analyzed it for evidence of themes related to the phenomenon of interest: reflective decision-making in elementary school engineering.

Participants in our study were the students and teachers in seven classrooms located in two urban school districts in different cities in the eastern United States. The student populations of the classrooms were culturally and racially diverse and had a high proportion (more than 50%) of students eligible for free or reduced lunch. Only students whose parents granted consent were included in data collection activities.

After completing a review of literature on engineering design cognition to determine the ways in which practicing engineers engage in reflective decision-making, we developed two paper-and-pencil tasks intended to create opportunities for the reflective decision-making discussed in the engineering design cognition literature. The planning task asked students to propose (by sketching and writing) two possible solutions for an object-retrieval design problem (Portsmore, 2011). The redesign task asked students to describe flaws in and revise a design for a plant cart. These tasks are not the focus of the study here, but participating students completed them before beginning *EiE* units in their classrooms. We conducted qualitative open coding (Glaser & Strauss, 1967) on data from these paper-and-pencil tasks looking for evidence of engineering reflective decision-making among students' written planning and redesign work. The themes that emerged from open coding of the planning and redesign tasks supported the six elements of reflective decision-making generated from our literature review (Table 1). We turned to the question at the focus of this study, do students also exercise reflective decision-making during the student-to-student interaction of collaborative engineering design projects? To confirm opportunities for all six reflective decision-making elements during classroom project work, we conducted content analysis of the EiE curriculum units. As discussed above, in Lesson 4 of all units, we found learning tasks that could reasonably be expected to call upon these six elements.

Partnering with four elementary teachers, we video recorded seven EiE units at four different grade levels (water filters in 2nd grade, bridges in 3rd grade, circuits in 4th grade, and maglev vehicles, windmills, pollinators, and knee braces in 5th grade). During each unit, we focused video recorders on one or two student groups. We also collected students' paper-and-pencil work on *EiE* handouts and images of their physical prototypes. After each unit, we reviewed the video footage looking for sustained student-to-student discourse that possibly exhibited the proposed reflective decision-making elements. We parsed the footage into episodes of student-to-student interaction. The duration of an episode was defined by the length of time a group of students remained focused on an activity or goal. Sometimes this focus only lasted for two minutes; sometimes it was 20 minutes or even longer.

Researchers brought video episodes to teacher/researcher meetings for analysis and discussion of whether the students' discourse exemplified one of the six reflective decision-making elements that had emerged from literature review and paper-and-pencil design tasks and had been confirmed in the *EiE* content analysis. A database stored information about all the video episodes and summaries of the group's discussion. From this database we identified thirteen episodes, from across all four classrooms and all seven units, where the teacher/researcher team had confirmed elements of reflective decision-making. Out of these thirteen, we used maximum variation sampling to create a representative sample of nine episodes in which roughly half were planning episodes and half were redesign episodes, and all four grade levels, all seven units, and all six reflective decision-making elements were included.

For in-depth analysis, we transcribed these nine episodes and coded student-to-student exchanges within the transcripts as examples of each of the six reflective decision-making elements. We cross-referenced all passages coded for same element to create definitions of what reflective decision-making looks like in practice among diverse urban elementary school students participating in a formal engineering curriculum. Finally, we chose one planning episode and one redesign episode to describe in case study format as illustrations of how students take up reflective decision-making elements during *EiE* units.

Table 2. Sampled video episodes

| *EiE* Unit | Grade Level | Students | Design Phase* |
|---|---|---|---|
| Bridges | 3rd | Boy and girl | Planning |
| Water Filters | 2nd | Three boys | Planning |
| Maglev Vehicles | 5th | Two boys and a girl | Planning |
| Knee Braces | 5th | Three girls | Planning |
| Windmills | 5th | Two boys and a girl (English language learners) | Planning |
| Hand Pollinators | 5th | Two girls | Redesign |
| Hand Pollinators | 5th | Girl and boy | Redesign |
| Knee Braces | 5th | Three girls | Redesign |
| Circuits | 4th | Boy and girl | Redesign |

* We recognize that design is not a linear process, and that initial planning of a design solution may involve nested moments of redesign, and that redesign after prototyping may involve a return to planning. Here we use "planning" to refer generally to the phase of work when students are determining what they will physically prototype, and "redesign" to refer generally to the phase of work after a prototype has been constructed.

## Findings

In our analysis of nine episodes of student-to-student classroom talk during the planning or redesign phases of seven *Engineering Is Elementary* design challenges, we found wide-ranging evidence of students engaging in six elements of reflective decision-making (RDM). This evidence took on different forms for grade levels and different design challenges. Here we briefly describe the range of student-to-student talk we found for each of the six RDM elements, and then we present two case studies to illustrate urban elementary students' reflective decision-making during planning and redesign.

### *RDM Element 1 – Articulate Multiple Proposals*

When we looked across five student teams working on five different *EiE* units, we found different ways that students took up the practice of collaboratively articulating and reviewing more than one possible way to solve the design challenge. Second graders deliberately asked team members to take turns describing design proposals for water filters, and fifth graders learning English as a second language similarly used explicit turn taking moves to solicit windmill blade design ideas. Third graders acted out multiple ways to use the same physical material for a bridge design. One team of fifth graders drew separate plans for knee braces with the stated intention of voting on the best, and other fifth graders looked at each other's work and clarified how one team member's proposal was distinct from others.

### *RDM Element 2 – Reflect on Strengths and Weaknesses*

The five student team episodes that we analyzed also revealed different ways in which students exhibited the element of reflecting on the strengths and weaknesses of design options. Students evaluated proposals according to constraints like the size of available materials or their limited strength, and according to criteria like the expected performance of a prototype in a specified amount of time. They also judged options according to other physical properties of materials and their own and their teammates' critiques about whether a proposed prototype would work or whether it would even be feasible to fabricate.

***RDM Element 3 – Intentionally Select a Potential Solution to Pursue***
To indicate purposeful selection of a design solution, some students voted explicitly on team members' proposals. Other ways in which plans were purposefully selected included indicating choice of proposal by writing a detailed materials list, assigning roles for making a shared design plan, shifting to consider details like number and dimension of materials, and synthesizing team members' ideas into a new merged proposal.

***Case Study of RDM During Engineering Planning***
To put into context these elements of students' reflective decision-making during engineering planning, we turn to the case of three second-grade boys working on the design of a water filter in the *EiE* unit *Water, Water Everywhere: Design Water Filters*. David, TJ, and Eliot face the task of creating a shared plan for a device that would clean the polluted water passing through it. On a previous day, they had investigated how coffee filters, sand, gravel, and wire screens interacted with dirty water, and they had been given time by their teacher to independently "Imagine" how they could combine these materials to make a successful filter. They are now sitting at a table with a bin of materials in the middle. They are set free to talk and begin to plan collaboratively. David describes his idea first. He states the materials he would use and starts to pick up one of the materials from the bin in the middle of the table. Viewing David's move to the materials bin as a premature jump in the design process, TJ and Eilot react strongly and reveal their focus on generating multiple ideas before beginning to build.

| | |
|---|---|
| David: | Yeah, you could put this ((referring to the coffee filter)) right in -- um |
| TJ: | No, we're meeting about talking -- fixing things together, David. |
| David: | I know, I'm going to put this ((referring to the screen)) over here ((on top of the 2-liter bottle)) and if we could // |
| TJ: | // No, no, no, listening together // |
| Eliot: | // No, talking to draw a picture ((pointing to a handout for planning the design)) // |

TJ and Eliot immediately try to stop David from picking up the material and tell him they are "meeting about talking," "listening together," and "talking to draw a picture." Although David might simply want to hold a material to help convey his design idea, we see in TJ and Eliot a commitment to reflectively making a collaborative decision based on a design space populated with multiple options.

Despite disagreeing over whether David should be handling the physical materials at this point in their work, the boys use the actual coffee filter to deliberate on the pros and cons of David's proposal. As they predict how the coffee filter might perform as part of the water filter, they consider the constraints of the available materials, including the size of the water bottle and the strength of the filter.

| | |
|---|---|
| TJ: | See, it doesn't fit. ((Attempting to display that the coffee filter will not fit into the 2-liter bottle)) |
| David: | Yes, it does, if you push it in there. |
| TJ: | No. |
| Eliot: | It will rip. |
| David: | Me -- me, and her and him did it before and it didn't rip. It just went through it. |

After TJ and Eliot convince David to return the coffee filter and water bottle to the materials bin, Eliot takes a turn stating his water filter idea, which is essentially to pass water through sand and gravel. He follows this proposal by immediately sharing his prediction of how it will work, which reveals implicit reflection on the key requirement of the design challenge (making water cleaner rather than "disgusting").

| | |
|---|---|
| Eliot: | Well, I think if would mix gravel, sand and // |
| TJ: | // And water. |
| Eliot: | It would make like a disgusting thing. And, like, I don't know. I don't know what it will do. Do you? Cause I don't know. |
| TJ: | Yeah, just mix the sand and gravel together. |
| Eliot: | Yeah. ((Chuckles out loud)) |
| TJ: | We're doing sand and gravel. |
| Eliot: | Yeah, but it will be so gross. |

On one hand, TJ and Eliot seem to take some delight in creating a water filter that makes "a disgusting thing," and therefore might judge the "gross" quality as a strength of Eliot's proposal. However, on the other hand, by saying, "I don't know what it will do. Do you?", Eliot also reveals a reflective stance about whether his proposed solution would meet design criteria.

Later in this episode, the boys continue to consider whether gravel should be part of their water filter, and with the teacher's support, TJ reveals reflection on the design criterion of water flow rate.

| | |
|---|---|
| Teacher: | // Wait, TJ had a question. Hold on, what was your concern? |
| TJ: | But if you did use the rocks, wouldn't it cover up that hole and the water would just stay in there. |
| Teacher: | You think even if he was just to use the sand it would be the same thing? Or you think it'd be ok with the sand? |
| TJ: | I think if he used the rocks, then it would cover up -- I still think if you use gravel that (…) it might cover the hole. |

At two points in the episode, TJ, Eliot, and David indicate an ability to intentionally select a shared design to pursue rather than to haphazardly put materials together. The first time this happens is right after each boy has stated his proposal for water filter materials. TJ suggests a strategy – voting – to determine how to move forward. This move fails, however, as David protests that not all proposals will receive fair consideration and refuses to go with the majority.

| | |
|---|---|
| TJ: | Let's vote. |

David: You're just gonna pick his, aren't you? ((Directed towards Eliot.))
Eliot: I choose TJ's.
David: I choose mine. I'm just going to choose mine.

At the end of the episode, with the teacher's support, TJ summarizes the team's predictions about how sand and gravel will interact with the water, and David says, "Okay, guys," to indicate consensus toward moving forward with a shared prototype.

TJ: We could, where we could take -- if we're going to mix it, we could block, uh, we could block the rocks (…)
Teacher: Okay, he's saying his is not going to block the rocks, meaning the hole. With the screen.
TJ: The screen would block the rocks from going in but the sand and water could still go in. But the rocks won't make it to block.
Teacher: Ok. You guys have a valid argument for real.
David: Ok guys I'm gonna put the water in here.

***RDM Element 4 – Re-tell Performance of Solution***
To make intentional decisions about how to improve their prototype, students first needed to become aware of its performance related to the requirements of the design challenge. We found several kinds of student-to-student talk that involved re-telling prototype performance, such as play-by-play narrating of test results while the test is occurring, describing flaws in a prototype while pointing to a design sketch, reminding team members what happened during a specific test, clarifying the nature of the flaws discovered during a test, putting test results in a positive light after a teammate expresses disappointment, and re-enacting the performance of a prototype.

***RDM Element 5 – Analyze Solution According to Specific Evidence***
Students drew on several kinds of evidence in a variety of ways as they iterated on their prototypes. They relied on critiques by fellow classmates to make sense of design flaws, interpreted what test results meant about the appropriateness of the materials in the prototype, pointed out how the user of a prototype would experience it, and proposed changes based on test results.

***RDM Element 6 – Purposefully Choose Improvements***
By talking about purposeful changes they were making to their prototypes, students indicated that they were making reflective decisions about redesign. Ways that students were purposeful with their improvements included altering their design sketch and justifying those alterations based on science principles, proposing a change of material based on the likelihood it would meet design criteria, using the rationale of usability or safety to justify new materials selection, demonstrating to each other the success or failure of a partially implemented design improvement, and soliciting team member cooperation in physically changing a prototype.

***Case Study of RDM During Engineering Redesign***
To illustrate elementary students' reflective decision-making during redesign, we move from second grade boys designing a water filter to fifth grade girls working on a hand pollinator in the *EiE* unit *The Best of Bugs: Designing Hand Pollinators*. In this design challenge, the goal is to

use common craft materials such as pipe cleaners, drinking straws, craft sticks, pom poms, erasers, and tape to make a device that can pick up and drop off as much pollen (modeled by baking powder) as possible. Different teams in the class have different model flowers into which their hand pollinators must fit, and Westria and Naomi have a three-quarter inch PVC elbow pipe fitting as their model flower. They create and test one hand pollinator based on their original shared plan to combine a craft stick and a pom pom ("fuzzy ball"), and they find that it delivers a very noticeable dusting of baking powder to the testing paper. Westria says to Naomi, "I don't think we need to improve," and Naomi responds, "No, this is good." Feeling like they are finished with the design challenge, they spend several minutes waiting at their desks for their teacher to be available so they can ask her what to do next. The first adult to arrive, however, is a researcher stopping by to ask how it's going. After hearing about their prototype and test results, she prompts them: "I bet you can think of a way that it could pick up *even more*. I bet there's something you could do to adjust it to pick up even more" Almost instantly, they shift from passive waiting into animated discussion.

> Westria: I don't think, what if we don't need to improve?
> Researcher: I bet you can think of a way that it could pick up *even more*. I bet there's something you could do to adjust it to pick up even more.
> (Naomi shakes head yes).
> Westria: (Gasp) what about a pipe cleaner?
> Naomi: (Shakes head yes). Oh like a pipe cleaner, you just (demonstrating with hands) like roll it around.
> Westria: You could put the fuzzy ball on it too.
> Naomi: So it picks up more.
> Westria: We could put the fuzzy ball after.
> Naomi: Except the wire would change this thing (demonstrates with hands).

When nudged by an adult's prompt, Westria and Naomi begin to reflectively make decisions about how to redesign their hand pollinator. When the researcher next steps by their table, Westria uses oral language to tell her about the revised design solution they have sketched on paper. The dialogue between Westria and Naomi leading up to this point makes it clear that the pipe cleaner is a very purposefully chosen improvement.

> Naomi: Oh (inaudible). The pipe cleaner's just like the fuzzy ball except it has metal in it so you can like wrap it around.
> Westria: So you can wrap it around and it'll pick up more on the pipe cleaner because (pointing to top of current design).
> Naomi: Where's the straw?
> Westria: You could build it this time.
> Naomi: So we don't need the wire, right?
> Westria: Ask for this paper.
> Naomi: I made another one.
> Researcher: You did? Tell me about this one.
> Westria: We think the pipe cleaner, because it's fuzzy too, like the fuzzy ball, will pick up pollen on the sides, (interrupted) will pick up pollen on the sides. And on the fuzzy ball, so like more pollen.

While the girls build and test their pipe cleaner and pom pom prototype, the researcher visits and again prompts them: "if you finish that, I wonder, what would happen, if you used something different than a purple pom pom, what do you think?" The girls respond to this nudge with a different element of reflective decision-making, where they begin to re-tell each other about the performance of previous possible solutions they have tried out.

> Researcher: And then, if you finish that, I wonder, what would happen, if you used something different than a purple pom pom, what do you think?
> (Girls together): Tape.
> Westria: No, wait, we tried it last time. It picked up a lot, but it didn't drop off. It's sticky.
> Researcher: Hmm. Tape has the property of being too sticky, huh?
> Westria: What worked last time?
> Naomi: The eraser, the eraser worked.
> Westria: A lot?
> Naomi: (Shakes head yes.) If you picked it up it dropped off a lot (demonstrating tapping).

They stop this conversation for a moment to finish recording a sketch and test results for their pipe cleaner and pom pom prototype. In the midst of drawing and writing, Westria suddenly returns to the conversation about what they will use for their third design. She is analyzing possible revised designs based on previous testing results, and she is re-telling how previous prototypes have performed. Her analysis and re-telling contribute to her reflective decision making about their next prototype.

> (Both girls writing and drawing on "Improve" handout about their second prototype.
> Westria: (Suddenly looks up.) Are we going to use the fuzzy ball or are we going to use the wire? The wire. The wire's pointy and we're never, if we, trust me. Trust me, I tried to do it with the pipe cleaner and the eraser, and it didn't work. The pipe cleaner kept on bending.

Westria then constructs a new hand pollinator out of stiff wire and a disc-shaped eraser and finds out that it "didn't really work." Undeterred, the girls move on to discuss and construct one final prototype, continuing to make decisions reflectively by re-telling about the performances of possible solutions, analyzing according to test results, and purposefully choosing improvements.

## Discussion

Using examples of language from student-to-student discourse about design plans and prototype improvements, our findings begin to characterize the nature of reflective decision-making for engineering design among urban elementary school students. We argue that the discourse of student team interactions reveals not only *that* elementary students are reflectively making decisions during engineering, but also *how* students are reflectively deciding. Data analyzed for this study suggests that during both planning and redesign, elementary students' reflective decision-making involves taking stock, analyzing, and moving forward. When conducting initial planning, students take stock of the range of possible solutions they've generated, and when redesigning, students take stock of (and re-tell) how prototypes have performed. This taking stock allows for measured analysis. During planning, students' analysis focuses on whether possible solutions might satisfy criteria and constraints, adhere to math and science principles, and respond to external critiques. During redesign, students' analysis seeks to make sense of testing results. This analysis allows students to move forward – at planning, with a choice of solution to pursue, and at redesign, with a purposeful improvement to the solution. This idea of taking stock, analyzing, and moving forward is a model of reflective decision-making provided by the language study conducted here.

Reflective decision-making can be considered a central component of engineering discourse, that is, of engineers' taken-as-shared ways of thinking, knowing, talking, representing, and working together. One of the reasons we look for reflective decision-making during engineering at the elementary school level is because we believe engineering design tasks can create a "third space" (Moje, Collazo, Carrillo, & Marx, 2001) where students can engage in personally meaningful but sophisticated disciplinary discourse (i.e., academic language) (Gee, 2004). We conducted this study, in part, to explore whether this belief was born out by evidence. In this way, our research is in the same family as other work that seeks to illustrate how elementary school engineering can transform what is possible for students, especially those who have been historically marginalized by mainstream school culture. For example, other research seeks to demonstrate that elementary engineering can shift the cultural production of "smartness" (Hegedus, Carlone, & Carter, 2014), help both teachers and students embrace failure (Lottero-Perdue & Parry, 2014), and position students as problem scopers not just problem solvers (Watkins, Spencer, & Hammer, 2014). We aim to show that elementary engineering can also enable sophisticated classroom discourse, including that associated with reflective decision-making. Here it is important to note that we studied classrooms that were not (at least at the beginning of the study) particularly noted as exemplars of elementary engineering education; and although the teachers had all experienced at least some professional development in the *Engineering Is Elementary* curriculum, before our study began, none had previously taught any of the *EiE* units. Therefore the reflective decision-making that we saw among students in all seven classrooms was possible even without experienced engineering teachers.

In our paper we have described specific episodes of data that elucidate six different elements of children's reflective decision-making during engineering design. To summarize our findings, we describe reflective decision-making in children's engineering as the multi-faceted practice of taking stock, analyzing, and moving forward. Our goal in characterizing children's reflective decision-making is to describe the behaviors, habits, or skills that might productively be emphasized as educators work to support elementary students in meaningful learning of engineering design practices. Here we have illustrated these with two case studies, one of planning and one of redesign. In later work we will describe the range of ways each element is taken up, across different grade levels, different English language learner status, and different *EiE* units as well as other curricular approaches to elementary engineering.

**Acknowledgements**

This research was supported by the National Science Foundation under grant DRL-1316762. Any opinions, findings, and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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