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Abstract

Although engineering design is dependent upon the use of science and mathematics, the actual prototype, model, or solution that pre-college students generate can be accomplished without the students explicitly using scientific or mathematical concepts. It is therefore important to explore how students apply science and mathematics concepts when engaged in a curriculum that was purposefully developed to foster student understanding of standards-based content. The purpose of this research is to apply the case study method to explore the following research question: *How do middle school students use scientific and mathematical concepts that were explored during the problem scoping lessons of an engineering design-based STEM integration unit to generate ideas and make design decisions?* Researchers collected data from one 7th-grade team during an integrated STEM unit and applied qualitative content analysis methods to examine the data. The findings show that students meaningfully used science and mathematics concepts taught within the unit to defend their engineering design ideas/decisions. It also revealed incomplete understanding of certain concepts. Engineering design can provide opportunities for teachers to assess how well students have learned scientific and mathematical concepts, provided that the curricula are carefully designed to prompt students' use of content to make design decisions.

Introduction

Engineering design as a way to teach science and mathematics in pre-college classrooms is becoming more and more prevalent. To help students engage in learning of science and mathematics, some pre-college teachers have turned to engineering as one possible natural integrator—helping students see spaces where their science and mathematics learning is relevant in the real world. Recent reform efforts in science and mathematics education, as shown in the Next Generation Science Standards (NGSS Lead States, 2013) and the Common Core State Standards for Mathematics (CCSSM; National Governors Association: Center for Best Practices, 2010), have included conceptions of engineering design, which further prompted the use of engineering design as way to teach science and mathematics. Engineering challenges can support students to meaningfully learn mathematics and science concepts through their application to realistic situations (Lou, Shih, Ray Diez, & Tseng, 2011; National Research Council [NRC], 2000). Thus, engineering provides opportunities for students to think critically about scientific and mathematical content. However, simply having an engineering design lesson does not guarantee that the intended critical thinking about content will happen. Research has also found that students can engage in engineering design and yet use very little unit-based scientific or mathematical content to inform their decisions (Mehalik, Doppelt, & Schunn, 2008; Siverling, Guzey, & Moore, 2017). Therefore, the design challenges should be structured in such a way that students must think deeply about content in order to design an effective solution. Without careful consideration of how the targeted scientific or mathematical concepts will be applied to generated solutions, it is likely that many students will design a prototype, model, or solution without actually building a deeper understanding of the concepts the unit was designed to target.

The purpose of our research is to explore how middle-school students connect the science and mathematics learned within an engineering design-based STEM integration unit to their engineering design solution. We examine how a team of students made design decisions when engaged in an engineering curricular unit that required redesigning a process to extract DNA to improve its effectiveness for collecting DNA in remote locations. By focusing on the redesign of this process, the unit was designed to purposefully connect the science and mathematics to the engineering design solution. Our research question for this study is:

How do middle school students use scientific and mathematical concepts that were explored during the problem scoping lessons of an engineering design-based STEM integration unit to generate ideas and make design decisions?

Background

Recent reform efforts call for the integration of scientific and engineering practices into science teaching. Engineering is uniquely positioned in this new science education approach since engineering can support student learning of science and development of 21st century competencies (Brophy, Klein, Portsmore, & Rogers, 2008; Lachapelle & Cunningham, 2014; NRC, 2012; Schnittka & Bell, 2011; Wendell & Rogers, 2013). Consequently, engineering practices and engineering design are embedded in pre-college science education standards and learning outcomes (Moore, Tank, Glancy, & Kersten, 2015; NRC, 2012; NGSS Lead States, 2013). However, there is no formal agreement on how engineering design and practices should be taught in pre-college science classrooms, and there are different approaches to engineering integration in science classrooms. The *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* report identifies three principles of engineering education (National Academy of Engineering [NAE] & NRC, 2009): Engineering education should emphasize the engineering design process, incorporate important and developmentally appropriate science, mathematics, and technology knowledge and skills, and promote engineering "habits of mind."

Engineering design, like the scientific process, is not one single process with a linear fixed set of steps to be followed by all engineers in all situations. Rather, engineering design is highly iterative and requires many decisions along the path to a solution (NAE & NRC, 2009; NRC, 2012). More specifically, "engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 104). While there are many approaches to design, at the core, design principles guide engineers as they identify needs and develop solutions, new processes, or complex systems. Engineers apply science and mathematics knowledge and use many cognitive skills as they design to develop products or processes. Simply put, engineers design solutions by making evidence-based decisions. Engineers also engage in reflective decision making as they identify problems, generate possible solutions, evaluate the outcome of each solution, and determine the best solution (Adams, Turns, & Atman, 2003; Crismond & Adams, 2012). Decisions in an engineering design context are influenced by controlled (e.g., availability of data) and uncontrolled conditions (e.g., environmental risks, safety) inherent in the design task. The quality of an engineering decision depends on what an engineer knows about the problem (knowledge), what can be done (options), and the desired outcomes (intentions; NRC, 2001). At the pre-college level, engineering practices involve: defining problems; developing and using models; planning and carrying out investigations; analyzing data; using mathematics and computational thinking; designing solutions; engaging in argument from evidence; and obtaining, evaluating, and communicating information (NRC, 2012; NGSS Lead States, 2013). These practices provide students opportunities to purposefully follow an engineering design process and develop skills or habits of mind such as critical thinking, collaboration, communication, and creativity (NAE & NRC, 2009).

While there is much potential for engineering design to serve as a mechanism for students to engage deeply with science and mathematics content, many factors influence whether or not inclusion of engineering is successful in promoting students' deeper learning of science and mathematics content. Some of the factors gleaned from literature include familiarity of the content to be applied, the need to provide justification, and explicit curricular or teacher focus on integration. Familiarity of the content to be applied was seen in a study (Valtorta & Berland, 2015) where students applied focal science and mathematics concepts to their pinhole-camera design only when the concepts were familiar (e.g., measurement). Although the teacher explicitly connected the novel science and mathematics concepts to the engineering challenge, students struggled to use them to support their design solutions. Related to the previous factor, providing scientific or mathematical justifications is not an inherent process (Purzer, Goldstein, Adams, Xie, & Nourian, 2015). One study (Azevedo, Martalock, & Keser, 2015) investigated students' written and verbal dialogue as they solved a given engineering challenge. Not surprisingly, the authors found that few students provided reasoning that contained targeted scientific and mathematical justifications for their engineering design. Another study (Purzer et al., 2015) found that when students balance design benefits and trade-offs through guided reflection and evaluation, they tend to develop scientific explanations. These are just a sample of several studies demonstrating the challenges of supporting pre-college students to explicitly invoke disciplinary knowledge and apply it to the design artifact (e.g., Berland, 2013; Guzey & Aranda, 2017; Jordan & McDaniel, 2014; Roth, 1996; Watkins, Spencer, & Hammer, 2014).

While the first two factors focused on the student, the final factor is related to curricular and teacher connections made to help students recognize the connections. An analysis of commercial engineering curricula that made claims about integration of mathematics found that the written curricula included conceptions of mathematics; however, these conceptions were only implicit (Prevost, Nathan, Stein, Tran, & Phelps, 2009). Prevost and colleagues (2009) argued that the mathematics concepts must be made explicit for students to learn the content in a meaningful way. Furthermore, not only must the curricula make connections explicit, but teachers must also frequently make connections between content and design explicit through both contextual classroom moves as well as connections between representational forms. Students tend to focus on the engineering event (e.g., the bridge gets stressed and broken during testing) rather than the mathematics and science concepts underlying the design features (Walkington, Nathan, Wolfgram, Alibali, & Srisurichan, 2014). Finally, teachers' emphasis on making these connections explicit have been found to increase student learning. Guzey and colleagues found that, over three years of teaching integrated STEM, a teacher went from implicit integration to more explicit integration, and each year, his students had more learning gains in the relevant science gains than the year before (Guzey, Ring-Whalen, Harwell, & Peralta, 2017). While these curricula and teacher pedagogical factors are not all of the factors encompassing the connection of standards-based content to engineering design, the literature presented here shows some of what is possible and some pitfalls to be avoided when implementing engineering integration targeted at increasing science and mathematics content knowledge.

To provide support and guidelines for teachers to teach integrated science and engineering effectively in pre-college classrooms, the NAE and NRC (2009) report on *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*, listed three implications: (1) Integration should be made explicit; (2) Students' knowledge in individual disciplines must be supported; and (3) More integration is not necessarily better. The literature presented above supports these implications. The NAE and NRC report also articulated that a real challenge to effective STEM integration is developing students' understanding of disciplinary content while also promoting connections across disciplines. Recommendation 1 states:

> In future studies of integrated STEM education, researchers need to document the curriculum, program, or other intervention in greater detail, with particular attention to the nature of the integration and how it was supported. When reporting on outcomes, researchers should be explicit about the nature of the integration, the types of scaffolds and instructional designs used, and the type of evidence collected to demonstrate whether the goals of the intervention were achieved. Specific learning mechanisms should be articulated and supporting evidence provided for them (p. 137).

Our research aims to address the nature of STEM integration by investigating pre-college students' design decision-making processes and their application of the science and mathematics learned within an engineering design-based STEM integration unit to their engineering design solution.

Method

This research used an exploratory case study design to investigate how students use science and mathematics concepts which were previously covered in their problem scoping lessons of an engineering design-based STEM integration unit to design a solution to the engineering problem. The case study methodology is notably advantageous when questions of "why" or "how" are being asked holistically of a real situation (Yin, 2014). The methodology allows for a deeper understanding of the genuine complexities of a system (Stake, 1995). In the current research, we applied case study methodology to glean unique insight into how students use science and mathematics as they participate in an engineering design challenge within an engineering design-based STEM integration unit.

Setting and Participants

This research study was conducted in a 7th-grade science classroom within a rural school district located in the Midwestern region of the United States. At the time of the study, the district had approximately 12,000 students, with 24% students of color, 15% of students participating special education services, 6% English language learners, and 37% receiving free/reduced lunch prices. The student data were collected from the classroom of a teacher who had 17 years of experience teaching middle school science. While this was the teacher's first experience implementing an engineering design-based STEM integration approach in her own classroom, she had previous experience with curriculum as a co-instructor with a researcher from our team for an in-depth summer professional development activity related to design-based STEM integration curricular units. The teacher taught a total of 5 sections, all 7th grade science with the same curriculum and lesson plans. Each class period was approximately 45 minutes long. One of the researchers on our team collected data in all 5 sections of the teacher's class. In each section, four or five student teams were audio recorded, with one of those teams selected to also be video recorded throughout the 3-week unit. Of the 5 teams across the 5 sections that had both video and audio recordings, one team was selected as a case for gaining a deeper insight into students' use of science and mathematics during the solution generation phase of an engineering design-based STEM integration unit. Due to absences from illness, field trips, state-mandated testing, and weather-related cancellations, all of the 5 teams had missing data. The team selected for this case study was among the most complete data of the 5 teams and was also recommended by the teacher because the members were particularly communicative with each other. The team chosen was a group of four 7th grade girls: Ally, Becky, Colleen, and Danielle (pseudonyms).

Development of the Integrated STEM Unit

Students in this study participated in the engineering design-based STEM integration unit *DNA Extraction Using Engineering Design: A STEM Integration Unit* (Mathis, Moore, & Guzey, 2015). This unit was designed to address the concepts and pedagogies identified in the STEM Integration Curriculum Assessment, STEM-ICA (Guzey, Moore, & Harwell, 2016; Moore, Stohlmann, et al., 2014; Moore, Guzey, & Brown, 2014). The STEM-ICA is a tool that operationalizes the STEM Integration Framework (Moore, Stohlmann, et al., 2014) to be useful in curriculum development and assessment. The STEM Integration Framework identifies components that are necessary to high-quality engineering design-based STEM integration in the classroom. High-quality STEM integration includes: (1) a motivating and engaging context; (2) an engineering design challenge through which the students engage in the practice of engineering design; (3) opportunities for students to learn from failure and redesign; (4) standards-based mathematics and/or science needed to complete the design challenge; (5) student-centered pedagogies to teach all STEM material; (6) explicit use of evidence-based reasoning by students to integrate engineering with the science/mathematics; (7) an emphasis on teamwork and communication; and (8) engineering design threaded throughout the unit as reasons to learn the mathematics and science, not just as a culminating project at the end of the unit.

At the time the DNA Extraction unit was developed, only six of the above components (1-5 and 7) were formally part of the STEM Integration Curriculum Assessment. While the DNA Extraction unit incorporated all 8 components, the results of this research and other studies (Guzey, Moore, & Morse, 2016; Mathis, Siverling, Glancy, Guzey, & Moore, 2016; Mathis, Siverling, Glancy, & Moore, 2017) led to the incorporation of evidence-based reasoning (6) and threading engineering design throughout a learning experience as a reason to learn mathematics and science (8) as key components of integrated STEM curricula. The issues that led to the addition of Components 6 and 8 were already becoming evident due to research on STEM integration curricula and thus were also taken into consideration when developing this unit.

The engineering design process used to frame this curricular unit was developed based on the *Framework for Quality K-12 Engineering Education* (Moore, Glancy, et al., 2014). This process of design contains six phases, which can also be categorized into two overall stages: problem scoping and solution generation. The first stage is called Problem Scoping and includes two phases, Define the Problem and Learn about the Problem (Background). During this time, students identify the engineering problem and learn more about the problem through a series of activities designed to help students gain background knowledge including lessons on the scientific and/or mathematical concepts that underlie the design. The second stage of the engineering design process is referred to as Solution Generation, which consists of four phases: Plan a Solution, Implement the Plan, Test the Solution, and Evaluate the Solution. During this time, ideation and planning are completed followed by students carrying out their plan and evaluating the effectiveness of their solution. Communication and teamwork are not associated with a specific phase; rather, they occur throughout the design process.

The Framework for Quality K-12 Engineering Education (Moore, Glancy, et al., 2014) and the STEM-ICA (Moore, Stohlmann, et al., 2014) support curricular units that allow students to learn core ideas of science through engagement in integrated scientific and engineering practices. This requires explicit integration of engineering into science, which provides more than just experience in design—it also provides support for science learning throughout the experience. Students learn science concepts and apply what they have learned from science lessons to the engineering challenge. Specifically, the teacher helps students see the connections between the science lessons and the engineering challenge; thus, the engineering challenge becomes more connected to science concepts. Since the DNA Extraction unit was built on the framework and assessment instrument mentioned above, the unit provides opportunities for meaningful and deep science and mathematics learning.

Table 1. Description of the lessons within the DNA Extraction unit

	Lesson	Days	*Key concepts targeted in each lesson* Lesson activities
Problem Scoping	1. Introduction to Engineering: The Problem	1	*Engineering: Identify the problem* Students are introduced to the problem through a document from the client, then discuss the client's needs and the importance of solving the problem. Students identify what type of information they need to learn more about.
	2. Cell Structure & Function	1	*Science: Cellular structures and functions* *Engineering: Understand the problem, gain background knowledge* Students use a 3D balloon cell model to identify the different structures found within a cell and discuss their functions. Using the same model, students demonstrate how DNA may be extracted from a cell.
	3. The Client's DNA Extraction Protocol	3	*Science & Technology: Biotechnology* *Mathematics: Percentages as applied to percent yield* *Engineering: Understand the problem, gain background knowledge* Students extract DNA from plant tissue cells based on the client's current protocol. This includes learning the procedures for the extraction as well as how to calculate the amount of DNA extracted.
	4. Maximizing Access to DNA	2	*Science: Relationship between cells and tissues* *Mathematics: Surface area* *Engineering: Understand the problem, gain background knowledge* Students use physical and graphical models to explain the relationship between the exterior and interior cells within a tissue and describe how this factor, surface area, influences the number of cells available to extract DNA from. Students discuss the relationship between cells and tissues as well as reflect on how this applies to the engineering problem.
	5. Understanding Competition: Enzymes*	2	*Science: Enzyme activity** *Engineering: Understand the problem, gain background knowledge* Students investigation how environmental factors such as temperature, pH, and surface area affect the enzyme's rate of reaction.
Solution Generation	6. Improving the DNA Extraction Protocol	7	*Engineering: Plan, implement, test, evaluate, redesign, and communicate solutions* Students design a process to improve the yield of DNA extracted from a plant tissue based on the client's protocol they performed in lesson 3. Students plan, test, and evaluate the success of their design by comparing the results to those they collected in lesson 3. Students then complete a second iteration of their design. Students decide on the protocol that best meets the client's needs and communicate their recommendation to the client.

*Note. Enzyme activity includes enzyme structure and function, as well as what factors affect their reaction rates. These concepts generally are found within high school science standards. However, it was necessary to introduce students to the concept of enzyme activity so they understood an additional element of the extraction process.

Description of Integrated STEM Unit

The DNA Extraction unit combines topics from cellular biology, biochemistry, and biotechnology through a series of STEM integration activities and concludes with students' design of an improved process for extracting DNA in the field. The context includes a client who works at a medical research firm that is trying to locate naturally-made compounds derived from plants that can be used to treat diseases in humans. DNA extraction from remote areas is necessary to send information back to the lab. The client's current DNA extraction procedure is not yielding enough DNA with the cost limits they have in place. Students are tasked with redesigning the procedure to improve the yield of the DNA extraction. Table 1 provides a description of each lesson in the unit. The unit is structured so that the students spend the first half of the unit working on problem scoping, which includes defining the problem (Lesson 1) and learning about the problem and relevant background information (Lessons 2-5). Each day during Lessons 2-5, students use an anchor chart to describe how what they have learned is related to the engineering solution they are preparing to design. The second half of the unit has students generating solutions to the engineering problem; i.e., the original extraction process does not yield enough DNA.

Data Sources

The focus of the current study is student use of scientific and mathematical concepts in the solution generation phases of the engineering design process. We purposefully chose to collect student data from the last lesson, *Lesson 6: Improving the DNA Extraction Protocol*, as this is focused on generating a solution. During the lesson implementation, we collected video and audio recordings of team discussions, as well as the associated students' artifacts from the lessons, shown in worksheets completed by the students. Data were collected for all seven days of Lesson 6; however, Day 4 had no usable data due to three of four members of the team being absent for a field trip. Further, Day 5's audio data did not capture all of the student team's conversations. This was due to the students moving outside of the proximity of the stationary audio and video devices while speaking or students from the case team talking in groups of other students, making the team's talk indecipherable. A video camera also collected data from the whole classroom, specifically set to capture teacher talk and whole group conversation. These recordings were examined to provide context and clarification for what was occurring within the teams but were not analyzed to address the research question.

Data Analysis and Reporting

To explore how middle school students applied mathematics and science concepts taught during the problem scoping lessons while generating solutions (Table 1), we utilized qualitative content analysis methods. Qualitative content analysis is a systematic way of analyzing documents, which may include transcribed communication, pictures, symbols, and written text to describe the meaning of the material (Krippendorff, 2013; Schrier, 2012). Qualitative content analysis can be used on material for which context is important and that requires some interpretation (Schrier, 2012). This method was chosen to allow us to holistically examine how students chose to use scientific and mathematical concepts during the solution generation stage of design.

Members of our research team transcribed the audio and video recordings verbatim. We then approached coding in multiple phases. During the first round of coding, we identified all instances where students used unit-targeted science or mathematics concepts in a written artifact or recorded conversation during the solution generation stage of the engineering design process. An instance was defined as a single phrase or sentence made by a student, though most instances were analyzed with consideration of their surrounding text or dialogue to fully understand the context of the instance. For example, the statement by a student that "cold speeded it up sometimes and heat slowed it down," taken alone does not provide enough information to determine if the student was using science content directly. However, when examining the conversations around this statement it became evident that students were talking about controlling enzyme reaction rates using temperature. Unit-targeted concepts were defined as those that were specifically addressed in the problem scoping lessons. These science and mathematics concepts are listed in Table 1 and include concepts such as enzyme activity, surface area, and percent yield. The example student statement given previously was thus coded with the unit-targeted science concept of *enzyme activity*. We then narrowed these data to include only instances in which the students *chose* to use the science and mathematics concepts. As a result, we eliminated any data in which students performed mathematics tasks that were required in the unit (e.g., measurements of mass and volume, percent yield calculations). In this way, we identified and narrowed the data to only include instances in which students chose to use scientific and mathematical concepts from the problem scoping lessons during the solution generation stage.

In the second round of coding, we coded each instance to determine what design ideas and decisions students discussed and wrote about when they used science and mathematics concepts. While the first round of coding was deductive because we categorized the instances using a pre-defined set of unit-targeted concepts, this second round was inductive because we explored the kinds of design ideas that students suggested. In other words, the categories for design ideas were not known ahead of time and emerged from the data.

Finally, we analyzed the data set to determine the relationships between the two types of coding categories: the science and mathematics concepts used and the design ideas posed. This analysis was done to determine how students used the scientific and mathematical concepts to generate ideas and make design decisions. For instance, the science concept identified in the previously mentioned example was enzyme activity, and the design idea was to alter the temperature in some fashion. These two items were then compared to identify the relationships between these codes. These relationships that emerged will be discussed further in both the Case Description and Discussion of Findings sections.

Coding was performed by two researchers on our team, with two additional members providing checks throughout the coding process. Our team has collective expertise in pre-college, as well as post-secondary, engineering, mathematics, and science. All of the researchers on our team who carried out or evaluated the coding contributed to the development of the curricular unit and thus were familiar with the science and mathematics concepts as well as the engineering design challenge. We coded all data to exact agreement.

The results in this manuscript are organized by the Case Description section, which is the traditional case study narrative (Yin, 2014) that includes both raw data and explanations of the context surrounding the data, followed by the Discussion of Findings section, which is set up to answer our research question by providing a cross-sectional view of the science and mathematics concepts from the problem scoping lessons in the unit that students invoked during the solution generation lesson. The Discussion of Findings section refers to the raw data presented in the case narrative to provide evidence to support the answers to the research question. Together these sections provide both a rich look into our data and a parsed view that will address the research question conceptually. Finally, we end with conclusions that provide implications for teachers, curriculum writers, and researchers as we consider how engineering can be used to help students learn science and mathematics deeply in integrated settings.

Case Description

Within the solution generation stages of the engineering design challenge, students in this team frequently chose to use the standards-based mathematics and science that had been addressed in the problem scoping lessons. They did this as they participated in completing the individual brainstorming worksheet, discussing planning within their team, filling out the team worksheet with their agreed-upon initial redesign idea, and discussing the initial redesign idea during testing. The data are presented and explained in chronological order. After a thorough description of the case, the Discussion of Findings section will highlight how students used standards-based mathematics and science across the data excerpts.

Individual Brainstorming (IB)

At the beginning of solution generation, students were asked to brainstorm individually three possible ideas for initially redesigning the DNA extraction protocol. Three of the four students in the team filled out their design ideas with pros and cons. Although Danielle, the fourth member of the team, recorded information on the worksheet, she did not address the prompt based on the design and therefore her response was excluded. Table 2 provides verbatim statements for Ally, Becky, and Colleen taken from the students' IB initial redesign worksheet.

Table 2. Individual brainstorming worksheet responses for initial redesign ideas

Ally	Idea 1: Instead of smashing it, we could cut it up in thin slices. - Pros: less cells will be smashed and ruined - Cons: less surface area Idea 2: The chemical we use to extract it, maybe cool it down to a colder temperature and it might have a greater effect. - Pros: The process would be faster if the temperature could impact it. - Cons: It could also have the opposite effect and make it take longer. Idea 3: Use less detergent substances - Pros: less cell would be killed, saves money - Cons: maybe not get as much DNA
Becky	Idea 1: Crush the specimen before extracting DNA. - Pros: more surface area - Cons: not as fast Idea 2: Cool down the specimen before extracting DNA. - Pros: faster, easy, and inexpensive - Cons: not as portable Idea 3: Use chemical to slow down enzymes. - Pros: You can take more time. - Cons: not eco-friendly, costly
Colleen	Idea 1: Cut up the sample with cells into tinier objects or mash them up. - Pros: more surface area with cells - Cons: could damage some useful cells Idea 2: Heat up the sample before extracting. Our recent experiment shows it helped. - Pros: slows down enzymes that might destroy DNA - Cons: extra time used up, heat could damage cells Idea 3: Pop the cell. The DNA is in the cell and nucleus so if we pop it, it will all be there. - Pros: fast, easy, simple - Cons: damage cell, enzymes could get in and destroy the DNA first

In total, the three students proposed nine design ideas. These ideas referred to three different types of alterations to the DNA extraction protocol: manipulating the plant tissue, changing the temperature, and altering the amount of chemicals.

The students independently considered manipulating the plant sample by breaking it into smaller parts either by cutting or smashing the plant tissue sample. Each of these three students identified that surface area would be increased by smashing the sample, which is a desirable quality in a design. However, both Ally and Colleen expressed concern about damaging or ruining cells. For Ally, this concern was strong enough for her to suggest cutting the tissue sample instead of smashing it, even though she knew smashing would yield more surface area. Furthermore, Colleen also discussed popping the cell as a means of accessing the DNA; however, she expressed potential negative consequences of popping the cell being that the enzymes may destroy the DNA before it can be extracted, and popping would damage the cell.

All three students also used science concepts when describing ideas that would alter the temperature of the plant tissue or the chemical environment surrounding it as a means of changing the rate of reaction. Colleen's idea was to alter the tissue sample directly by increasing the temperature. Based on a previous experiment, she inferred that increasing the temperature would "slow down the enzyme that might destroy DNA." Alternatively, Becky and Ally wanted to reduce the temperature of a component in the extraction protocol. Like Colleen, Becky's focus was manipulating the temperature of the sample directly; unlike Colleen, Becky suggested cooling the specimen down. Ally, on the other hand, wanted to decrease the sample's temperature indirectly by changing the temperature of the extraction chemicals that came in contact with the tissue sample. Becky indicated that decreasing the temperature of the tissue sample would make the process "faster," but Ally was unclear as to what effect a decreased temperature would have. She wrote both "The process would be faster if the temperature could impact it," and "It could also have the opposite effect and make it take longer." Ally and Becky both thought that decreasing the temperature of either the tissue sample or surrounding chemicals would influence the rate of reaction, but neither elaborated further on how or why that would occur.

Another design idea that two of the students considered was altering the environment by adding or removing chemicals. Becky contemplated adding a chemical to the solution that would reduce enzyme activity. Ally wanted to reduce the amount of detergent, which was the chemical responsible for breaking open the cell membrane, even though she acknowledged that it would yield less DNA available for extraction.

Team Planning Discussion (TPD)

After completing the IB worksheets, the students participated in planning within their team. These discussions consisted of the students sharing their individual ideas (Table 2), sharing new ideas, and attempting to come to consensus on what they would implement as their initial redesign of the DNA extraction protocol. The excerpts that include evidence of students using standards-based science and/or mathematics content that was covered during the problem scoping lessons are presented chronologically.

The first discussion excerpt (TPD-1) shows students focusing their conversation on manipulating the plant tissue sample—in particular, slicing vs. smashing the plant tissue. The students used ideas of surface area and damaging cells and DNA as they debated whether smashing or slicing the sample would yield more DNA during extraction.

> **TPD-1**
>
> Ally: Ok, so one of my ideas was instead of smashing the strawberry, or whatever we are using, we could cut it up into a bunch of really, really thin slices.
>
> Colleen: That's what I said too.
>
> Ally: Oh, you did. And I said less cells would be ruined or smashed … but since we are not smashing, it would be less surface area. It is better than doing nothing, but smashing will ruin the cells.
>
> Becky: But, we can't put the cells back.
>
> Colleen: It is better to do it that way because if we do, if we are smashing we're going to have less cells.
>
> Ally: If we cut them into thin slices ...
>
> Becky: How would we have less cells?
>
> Colleen: Because we kill them.
>
> Becky: No, like … the cells need to be broken open so we can get to the DNA.

In this example, Ally, Becky, and Colleen used science content related to surface area and cell death to provide reasoning for why the group should choose one method or the other. Ally and Colleen were both concerned that smashing the tissue sample would ruin and kill the cells within. Throughout the conversation, Becky tried in different ways to help her teammates understand that the cells from which the DNA gets extracted will not survive. In this first excerpt, she gave evidence for why the cells will die (i.e., the cells need to be broken open so we can get to the DNA). -Later during the discussion, the students continued sharing more ideas from the IB activity. In this second excerpt (TPD-2), the students presented the same basic information that they wrote on the IB worksheet but added more detail. Here we see students focusing on changing the sample and surrounding environment as they discuss their ideas.

TPD-2

Ally: If we change the temperature of the … detergent or something. Like make it colder so then it could go faster. But we could also, slow down the process.

Becky: I said we could freeze the thing [tissue sample] like we did over there. [Pointing to the location where they completed the enzyme lab.] It would not take very long to freeze it because it would be small, easy, and inexpensive, but it's not as portable because you can't like, carry a freezer around.

Danielle: Yeah, that is what I put.

Becky: And then I said crush whatever you are doing so there is more surface area and it's not expensive but it wouldn't be as fast as like dropping something in it. And my third one, was use the chemicals to slow down the enzymes but figure out how to do that without slowing down the ..., or not killing the DNA. Like pros, you could like, take your time with it, you don't have to like, rush. Then it's not as eco-friendly, it's costly, and it might hurt the DNA.

Danielle: I got mostly the same as Becky, about half of it.

Colleen: I put heating up the sample because I wanted to slow down the enzymes. But then you could also cool it down because then it would bubble more and you'd get more of a reaction too.

Like in the IB responses, three of the students in this discussion noted that altering the temperature would be a plausible design solution. However, each approached the temperature alterations differently. Two students focused on manipulating the temperature of the tissue sample, and one wanted to change the temperature of the environment. First, Ally suggested manipulating the temperature of the environment by cooling the detergent that breaks down the cellular membranes to make the reaction work faster. However, she also noted that this might slow down the process, though she does not clarify what she means by the term "process." Next, Becky shared her design idea about freezing the plant tissue sample, pulling from her experiences with the enzyme lab where she found it should slow down enzymatic activity. She also pointed out that this would meet many, but not all, of the engineering criteria (i.e., it would be small, easy, and inexpensive, though not portable). Finally, Colleen proposed two competing ideas related to changing the temperature of the sample. She first suggested heating it, using a decrease in enzyme reaction rates as her justification. However, she also suggested cooling the sample to "bubble more," which would get "more of a reaction." Colleen did not clarify what reaction she hoped to get more of.

In TPD-2, Becky also presented two other ideas, one related to manipulating the tissue sample and the other about adding a chemical to the surrounding environment. First, she brought back up the discussion about smashing the tissue sample to increase surface area. Then, she introduced her final idea from brainstorming, which was to add chemicals to the environment to slow the enzyme rate, though she expressed concern that the DNA may be damaged by this. Later, the students returned to their previous disagreement about which design idea to choose related to manipulating the plant tissue sample (i.e., smashing or slicing). The next excerpt (TPD-3) shows this conversation, which is a continuation of some of the themes from TPD-1.

TPD-3

Colleen: I think we should cut it [the sample] because smashing it would kill the cells.

Becky: I don't understand how that would kill the cells though.

Colleen: Because if you smash a cell, it would like pop it open and it dies.

Becky: Yeah, but it's going to die anyway.

Colleen: If we do it the smashing way, it will give the enzymes more time to get to the cell, the DNA and destroy it. Because what the enzymes do is destroy the DNA.

Becky: Hey, but how does smashing it give it more time than cutting it?

> Colleen: ‘Cause smashing it would like be feeding it I guess. And cutting it really small where like the inside of those might still be cells.
>
> Becky: But the cells are going to die anyway.
>
> Colleen: But cutting they'll die slower. That sounds horrible.
>
> Ally: We're smashing them.
>
> Colleen: Okay.

Here, the students used different scientific ideas to support their viewpoints. Colleen suggested slicing the plant tissue as a way to mitigate killing the cells. She first justified this by stating that smashing the cells will kill them. Then, she moved to a more sophisticated justification, relating smashing cells to allowing more time for the enzyme to “destroy the DNA.” Similar to TPD-1, Becky countered her justifications by repeatedly stating that regardless, the cells would die during the DNA extraction process. Although Ally initially presented the idea of cutting the plant tissue into thin slices (see Table 2 and TPD-1), by the end of the discussion Ally had decided that smashing was the better choice for the improved DNA extraction protocol design.

The final excerpt, TPD-4, shows that students returned to the ideas presented in TPD-2. Specifically, students considered how they were going to change the temperature to influence the enzyme reaction rate, while keeping in mind the materials they had access to.

> **TPD-4**
>
> Colleen: We can use a hot plate because cold speeded up enzyme, heat slowed them down.
>
> Ally: Which one do we want though? Do we want to heat it [the solution] up or do we want to cool it down? It depends on if we want the enzymes to go faster or slower? So, let's use the heat, hot plates.
>
> Colleen: If we cool it down, it will go fast; it will go faster but if we heat it, there is the chance that it will break down the DNA instead.

In this conversation, members of the team were debating whether they should increase or decrease temperature. Colleen brought up the idea of using a hot plate, stating that hotter temperatures would slow down the enzymes (i.e., the desired effect) and cold would speed them up. Ally acknowledged that heating or cooling the solution would cause the enzymes to “go faster or slower,” but she questioned which of those was a desired effect. Ultimately, she decided that heating the solution was the best option. At this point, Colleen agreed and still wanted to heat the sample since cooling it down would cause the enzymes “to go fast.” However, she did add a note of caution that heating it might increase the risk of destroying the DNA before it could be extracted.

Final Team Decision (FTD)

After two class periods of discussing design ideas for their redesign of the DNA extraction protocol, the team decided upon two changes to make to the protocol, both of which involved standards-based science and mathematics concepts from the problem scoping lessons. At this point, the team was asked to complete and turn in their design plan for review by the teacher. Table 3 provides the verbatim text from the team’s worksheet.

Table 3. Team initial redesigned DNA extraction protocol plan worksheet responses

- We are going to smash it to get more surface area and more cells. - We also will change the temperature to affect the DNA-destroying enzymes. - We will heat up the DNA to slow down the enzymes. It seems more effective and it wasn’t in the original protocol.

Here, we see that the team recorded their decisions to manipulate the sample in two ways. The first was to smash the plant tissue sample. The justification provided for smashing the plant tissue was because smashing increases surface area, which means that more cells are exposed to the environment. The second recorded design decision was to increase the temperature, although the students did not indicate if they were referring to the solution, the tissue sample, or both. They proposed heating as a means to slow the rate of reaction of the "DNA-destroying enzymes."

Testing Solution Discussion (TSD)

After finalizing the changes that they wanted to make to the initial redesign of the DNA extraction protocol**,** the team tested their new protocol. Once they collected their tissue sample, it was clear that they had not discussed how and when they would smash and heat the sample. After a short conversation with the teacher about how to heat the sample safely on a hot plate, the team decided first to combine the sample and extraction solution, then smash both together, and finally place that mixture in a hot water bath to heat it. During most of this part of the testing process, the discussions that occurred related to the semantics of performing the extraction. However, one conversation did emerge that contained standards-based science content related to the learning objectives of the problem scoping lessons. This conversation can be seen in the following excerpt (TSD). Immediately prior to this conversation, students had placed the tissue sample and extraction solution into a plastic bag. The excerpt occurred as students smashed the bag's contents.

TSD

Becky: You're going to make it [the baggie] explode.

Colleen: Don't smash it 'cause there's thing. We need the DNA in there and she said ...

Becky: She said it won't kill it 'cause isn't not a living thing. At all. It'll just break it.

Colleen: It will kill the enzymes.

Becky: No, it won't. Enzymes aren't living.

This excerpt shows that there was still some disagreement about whether or not smashing the sample was the best option, as Colleen was concerned about killing contents of the cell. She first expressed concern for the DNA and then later enzymes. Becky attempted to correct her concern by telling Colleen that the DNA and enzymes aren't living things.

Rest of the Case

After testing the initial redesign of the DNA extraction protocol, the team evaluated how successful their initial redesign was. Following this, the students completed a second round of redesigning their DNA extraction protocol, including a team planning discussion, implementing and testing the second redesign, and doing a final evaluation. While these transcripts did contain written and verbal instances of students using science and mathematics, they were all related to performing the required measurements and data analysis tasks. Therefore, these instances were not included in this case description.

Findings and Discussion

The above case narrative provided the overall case that students used mathematics and science within the solution generation stage of their engineering design challenge. To answer our research question *How do middle school students use scientific and mathematical concepts that were explored during the problem scoping lessons of an engineering design-based STEM integration unit to generate ideas and make design decisions?* more completely, we present a discussion of our findings in terms of the mathematics and science concepts and the design ideas in which they were used.

While redesigning a new DNA extraction protocol, students were able to apply scientific and mathematical concepts from all four science- and mathematics-focused lessons of the engineering design-based STEM integration unit. These science and mathematics concepts included cell structure and function, surface area, and enzyme activity (i.e., the role of enzymes and how to affect their reaction rate). The students elected to apply these concepts to defend their design ideas, which ultimately assisted them in making design decisions. In other words, they used science and mathematics concepts to justify, or provide reasoning for, design possibilities. A summary of the relationships between the problems students were attempting to address, their design ideas, the standards-based science and mathematics concepts used as justifications, and the science lesson in which those concepts were taught is shown in Table 4.

When students generated design ideas independently, they used mathematics and science from previous lessons in the unit to justify their ideas. In this activity, three of the four team members generated three ideas each for a total of nine design ideas. However, one of the design ideas, Colleen's idea to "pop the cell," was not an enactable design idea. In other words, she did not provide a macroscopic mechanism by which this could be done in the DNA extraction protocol, instead merely indicating that it was an event that needed to happen on the microscopic level. It was found that some of the remaining eight design ideas overlapped, reducing the total of unique design ideas posed to six. During the discussions and writings that followed, no new design ideas for which the students used science and mathematics as justification were presented. Therefore, the six-major science and/or mathematics-supported design ideas posed by the students during the solution generation phase are summarized in Table 4.

Table 4. Relationship between design ideas and science and mathematics concepts

Problem to be Addressed	Design Idea	Standards-based Science and/or Mathematics Concepts	Problem Scoping Lesson
Accessing the DNA	Smash tissue sample	Cellular structures & functions, Surface area	2, 4
	Slice tissue sample	Cellular structures & functions, Surface area	2, 4
	Reduce amount of detergent	Cellular structures & functions, Purpose of steps in the extraction process	2, 3
Preserving DNA's structure	Increase temperature	Enzyme activity	5
	Decrease temperature	Enzyme activity	5
	Add a new chemical	Enzyme activity	5

Based on the students' mathematics and science justifications for the design ideas, the six design ideas can be placed in two categories related to the problem that the students were trying to solve with their design idea. They indirectly identified two problems, or potential areas of improvement, in the original DNA extraction protocol: needing to access the DNA and needing to preserve the DNA's structure. As seen in table 4, students posed three different design ideas in an attempt to access more DNA for extraction and three different design ideas that would prevent enzymes from destroying the DNA.

The remainder of this discussion section is organized first by the problems students were attempting to address. Because the two problems are deeply connected to students' mathematics and science knowledge, the next level of organization is the science or mathematics concepts students used. Finally, we describe how the science and mathematics concepts were used to defend the six design ideas and ultimately help the students make decisions for the redesign of the DNA extraction protocol.

Problem 1: Accessing the DNA

The first problem the team attempted to address in the extraction protocol was identifying a way to maximize access to the DNA within the tissue sample. Students generated three design ideas to accomplish this: smashing the sample, slicing the sample, and manipulating the amount of chemicals used. The team applied two science and mathematics concepts as they considered how to maximize the amount of the DNA they could access and remove from the cells: surface area and cellular structures and functions.

Surface Area

When talking and writing about the design ideas of smashing and slicing their tissue sample, one concept students considered was surface area. While this concept is important to science, it is also a fundamental concept in mathematics. In individual brainstorming (Table 2), two discussions (TPD-1, TPD-3), and their final redesign artifact (Table 3), there is evidence that all students agreed that the more the tissue sample was smashed, the more surface area there would be. During lesson 4 of problem scoping, students had learned that breaking a volume of a sample into smaller pieces increases the surface area of that sample, and we see them applying that correctly during solution generation. Only exterior cells, i.e., those on the surface, are exposed to DNA extraction solution and therefore are the cells most likely to break open to release the DNA. The artifacts and conversations cited indicate that students applied their conceptual understanding of surface area to justify their design ideas as a means of increasing the number of cells in the tissue that DNA could be extracted from.

Cellular Structures and Functions

Another science concept that students considered was cellular structure. Specifically, the students identified the need to remove the DNA from within the cell, and they proposed three solutions related to this goal. The first two design ideas were about manipulating the tissue sample: smashing it or slicing it. In addition to the surface area concept described above, both of these ideas tied to lesson 2. In lesson 2, students used a three-dimensional model to learn that DNA is located in the nucleus of a cell and that both the nucleus and cell have membranes that need to be broken for the DNA to be accessible. The third design idea proposed was related to cell structure and function was Ally's idea to reduce the amount of detergent as a means to kill fewer cells (Table 2). This design idea is tied not only to lesson 2 but also to lesson 3 since it was in that lesson that the students learned that the detergent is a chemical means for popping the cell.

While smashing or slicing the tissue sample were design ideas that increase the number of cells exposed to the detergent and thus broken open, the students recognized that this would also make DNA more accessible to other structures in the cell (Table 2, TPD-3). For example, during the planning discussion, Colleen suggested that smashing might not be the best option because, "If we do it the smashing way, it will give the enzymes more time to get to the cell, the DNA and destroy it. Because what the enzymes do is destroy the DNA." This ties to the science and mathematics concepts from lesson 2 and lesson 5. In lesson 2, students learned that a specific enzyme (DNase) is located in the cytoplasm of the cell, and the DNA is located in the nucleus. As such, these two cellular components do not regularly come into contact with each other, but they do once the nuclear membrane is popped. Later in lesson 5, the students learned that this particular enzyme is responsible for decomposing DNA that it comes into contact with.

Interestingly, students' discussions about the design ideas of smashing and slicing revealed that some students were trying to preserve the life of the cell, even though they acknowledged that the cells need to die to access the DNA (Table 2, TPD-1, TPD-3**)**. This ultimately caused these two ideas, slicing and smashing, to unnecessarily become competing ideas. For instance, Colleen showed concern for damaging the cell even as she stated that popping the cell and nucleus would be necessary to extract the DNA. She and Ally seemed to want to pop open a cell while also trying to preserve the life of the cell. This conflict was not the case for Becky as she explained that "the cells need to be broken open so we can get to the DNA," and pointed out that regardless of what they did, "the cells are going to die anyway."

Problem 2: Preserving DNA's Structure

The second problem the team wanted to address was reducing the amount of DNA destroyed during the extraction process by controlling the enzymes in the tissue sample. Students generated three ideas to accomplish this: increasing the temperature, decreasing the temperature, and adding a new chemical that would slow down the enzymes. The team primarily applied science concepts related to enzymatic activity as they considered how to keep DNA intact so that it could be removed from the cells.

Enzyme Activity

The team agreed that temperature was a plausible way to change the tissue sample and/or environment. The students understood that changing the temperature, either by increasing or decreasing it, was an option that had the potential to influence the amount of DNA extracted (Table 2, TPD-2, TPD-4). However, only one student used her understanding of enzymatic activity as a justification for changing the temperature of the environment. Colleen suggested "heating up the sample because I wanted to slow down the enzymes" since increasing the temperature may "slow down the enzyme that might destroy DNA," which highlights that she applied her understanding of enzymatic activity to the design solution. The students drew on their experiences from lesson 5, when they learned that manipulating the environment has the potential of slowing or stopping enzymes. During this lesson, students had carried out enzymatic reactions at three temperatures: cold (ice-water temperature), room temperature, and hot (boiling-water temperature). They observed the amount of bubbles created in each chemical reaction to qualitatively measure the effect of temperature on enzyme reaction rate. They collected data showing that reactions at room temperature went faster than reactions at cold temperatures, which is consistent with reaction rates generally increasing as temperature increases. They also observed that the reaction rate at the hot temperature was the slowest, which occurred because the enzymes had become denatured due to the heat. The data students collected during lesson 5 were consistent with science concepts. However, the students' application of the enzymatic activity data and concepts seemed to be incomplete. They stated that hot temperatures slowed the reaction down, which was consistent with their data and the underlying science concept, but there was disagreement about whether the cold would speed it up or slow it down (Table 2, TPD-2, TPD-4). It was unclear if students were taking into account the full data set or only comparing reactions at hot temperatures with those at cold temperatures.

The third design idea that was considered for manipulating enzyme activity was to add a chemical to the DNA extraction protocol. Becky stated that she wanted to add a "chemical to slow down the enzyme" and thus hinder the enzymes' ability to break down DNA (Table 2, TPD-2). Here, she suggested another way to control enzymes based on her observation in lesson 5 that some chemicals can affect enzyme function. Though this was a valid design option, the student team did not pursue this further. One possible reason this idea was dismissed early on may have been because only one student generated this idea as a means of slowing down enzymes; in contrast, all of the students had identified changing the temperature as a way to achieve a similar effect. Another possibility is that some of the students had an incomplete understanding of how chemicals might affect enzyme activity within the DNA protocol and therefore chose a path they were collectively more comfortable with.

Applying Multiple Science Concepts to a Context

For most of this section, we discussed scientific and mathematical concepts individually to better understand how students used each concept to generate ideas and make design decisions. However, concepts are not isolated in real life. Because they are not isolated, students can have correct ideas about one concept and incorrect ideas about another concept, but these ideas can show up together. In this unit, Colleen and Ally made statements that were correct in isolation, but when combined and in context it is clear that the students did not fully understand the big picture of the science behind the DNA extraction process. For example, Ally, Colleen, and Becky all wrote or made statements about the following concepts: smashing the tissue sample would yield more surface area than slicing it or leaving it whole, and high surface area is desired; smashing the tissue sample would ruin or kill more cells; and cells die when they are popped open. Individually, these are all correct conceptions about the DNA extraction process. However, Ally and Colleen both initially resisted smashing the strawberry because of their concern about damaging the cells. They did not seem to understand that the cell membrane would have to be popped, causing the cell to die, for the DNA to be extracted. In this instance, the students used several correct ideas about surface area and cell structure and function to justify their design ideas, but they also revealed an incomplete understanding of the science of DNA extraction.

Conclusion

In this case study, we found that a team of students meaningfully engaged with several standards-based scientific and mathematical concepts from the problem scoping lessons of the unit while making design decisions during the unit's solution generation lesson. The case study allowed for deeper insight into how students used science and mathematics when engaging in the solution generation stage of an engineering design process by allowing the researchers a unique look into how students actually applied content when making design decisions. For this case study, we found that each of the design decisions students considered resulted in students applying standards-based science and mathematics that was learned during the problem scoping portion of the unit.

This case demonstrates that a carefully designed STEM integration curriculum has the potential to encourage students to make meaningful connections between the disciplines of STEM, particularly in the application of science and mathematics to engineering. This curriculum intentionally sought to foster students' engagement and application of standards-based concepts and lessons, rather than making the assumption that students would apply knowledge about relevant science and mathematics taught earlier in the unit. In particular, there were two factors about the development of this engineering design-based STEM integration curriculum that seemed to help students apply standards-based science and mathematics concepts during engineering solution generation. First, the engineering challenge was carefully chosen to align well with standards-based science and mathematics concepts. Although the students considered other factors during design (e.g., cost, portability), it was essentially required that they use science and mathematics since they needed to redesign a DNA extraction process. This is in contrast to units in which the engineering design problem can be accomplished without use of the desired science and mathematics content (Azevedo et al., 2015; Valtorta & Berland, 2015). This finding supports the claim that the curricula need to be designed carefully to allow students to transfer their knowledge of scientific and mathematical concepts to the engineering problem (Guzey & Aranda, in press; Siverling, Guzey, & Moore, 2017).

The second curriculum design factor that helped students apply science and mathematics concepts to engineering design was the explicit inclusion of scaffolds for evidence-based reasoning, which is one of the tenets of the STEM Integration Framework (Moore, Stohlmann, et al., 2014). In other words, the unit was written such that students were asked to justify their design ideas and decisions. For example, the individual brainstorming worksheet required students to think about and write down not just their initial design ideas, but also the pros and cons of each. In Table 2, most of the science and mathematics concepts were found in the pros and cons statements rather than the design ideas themselves. This use of evidence-based reasoning was also found during the student team's conversations; they often used the science and mathematics concepts of the unit to defend their design ideas and negotiate until they reached a decision about a design feature. While other tenets of the STEM Integration Framework (Moore, Stohlmann, et al., 2014) likely also contributed to the students' ability to use standards-based science and mathematics concepts while designing a solution to an engineering problem, the built-in evidence-based reasoning scaffolds seemed to have a particularly noticeable effect.

By digging deep into the students' discussions and artifacts, we were able to view an entire team's engineering experience and examine how this team invoked science and mathematics content. The discussions and worksheets also revealed certain incomplete understandings that may not have been obvious without the engineering design challenge. These findings are in line with previous research suggesting that engineering design can provide opportunities for teachers to assess how well students have learned scientific and mathematical concepts (Penner et al., 1998; Valtorta & Berland, 2015). Additionally, because the students' attempts to apply scientific and mathematical concepts to solve an engineering design problem occurred in a collaborative setting, they were not just faced with their misconceptions, but they had the opportunity to work through and correct them with their peers. This aligns with previous research that suggests the socially constructed practices of solving engineering problems can help students learn (Guzey & Aranda, 2017; Roth, 1996).

This study begins to reveal strong evidence that this team of students used standards-based science and mathematics to defend their design ideas and decisions, but these findings are not necessarily generalizable to other teams who engaged in this same engineering design-based STEM integration unit or in other similar curricula. Learning is a complex endeavor that includes many factors that have the potential to influence student learning. A limitation of this study is that even though it focused on one team of students and their interactions, it did not explore how the teacher or other factors may have influenced the students' use of mathematics or science as they generated a solution to their engineering problem.

It is recommended that further studies be done to examine if students apply science and mathematics within other engineering design-based STEM integration curricula. By focusing on one student team, we were able to deeply examine multiple forms of data generated over the course of a whole unit. This level of detail was needed to understand fully how students integrated science and mathematics into their engineering design in a natural setting. However, additional research should consider other approaches such as comparative-cross-case analysis and student interviews to determine whether these findings are consistent across other cases and to better understand to what degree students were applying knowledge they had learned during the course of the unit as compared to knowledge they may have acquired prior to the unit. This also may help provide insight as to how the lessons supported student learning and why they may not have developed a complete understanding of a particular concept. In addition, assessment measures capable of capturing students' use of disciplinary knowledge integrated with engineering could be used to study effectiveness of curriculum on a larger scale. Finally, another avenue of future research could explore curricular implementation of engineering design units that focus on building an object vs. developing a process to see if one encourages students to connect the mathematics and science better than the other.

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