Content Analysis of Middle School Students' Argumentation in Engineering

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In recent decades, argumentation has emerged as a major trend in K-12 science education.[1, 2] Its proponents assert that argument-driven science education fosters conceptual understandings of the nature of science and can increase students' proficiencies with core scientific practices.[3,4] With the advent of the *Next Generation Science Standards (NGSS)*,[5] middle school students are expected not only to engage in argumentation about the natural world, but also to construct or refute claims related to solutions about the designed world (see *Science and Engineering Practices* related to MS-ETS1-2). In practice, according to the NGSS, middle school students can construct and justify claims about which engineering design solutions should be adopted.

Though instruments have been developed and validated for assessing middle school students' learning progressions in argumentation in science,[6] comparable instruments have not been developed and validated for assessing students' argumentation in engineering. The purpose of this exploratory study was therefore to identify components of middle school students' arguments specific to engineering, and to begin to develop an assessment instrument that accounted for these specific elements. To achieve this goal, we conducted a content analysis of 69 middle school students' writing samples when asked to write an argument on behalf of their proposed engineering design solutions. We identified common patterns across their writing, and used these patterns to propose categories for a rubric that accounted for different dimensions of argumentation specific to engineering. In the following sections, we situate our study within previous empirical and theoretical literature, and then we describe the context in which the study was conducted and the methods by which the data were analyzed.

Related Literature

Across various branches of science, K-12 students who engage in argumentation often develop better understandings of scientific content and of the nature of science when compared with students who do not engage in argumentation.[3, 7, 8] The most common model of argumentation in educational settings, which has been widely applied across academic disciplines, is Toulmin's model.[9,10] This model includes—among other elements—constructing *claims*, supporting these claims with *evidence*, and providing *rebuttals* to counter-arguments.

While praising the utility of this model, Sampson and Clark nonetheless warned that *domain-general* models of argumentation, such as Toulmin's, may not adequately capture *domain-specific* methods of knowledge production and communication.[11] This warning is echoed in a wide body of empirical and theoretical literature in disciplinary literacy,[12,13] which has maintained that each academic discipline has established its own standards of evidence for what constitutes valid claims. Consequently, more domain-specific methods of assessing argumentation are needed in order to determine the validity of claims according to discipline-specific standards of evidence.

Instructional Practices that Foster High-Quality Argumentation in Engineering

Mathis and colleagues recently asserted that "currently, almost no research regarding argumentation in K-12 engineering education exists" (p. 2).[14, 15] To address this dearth of research, they conducted exploratory studies with elementary and middle school students, which demonstrated that even young students are able to engage in complex argumentation across multiple instructional units when these units are scaffolded properly. Specifically, Mathis and colleagues identified two conditions that led to student argumentation: teacher questions that begin with *Why?* instead of *What?* in discussions about students' proposed engineering designs, and opportunities for students to brainstorm and negotiate solutions in small groups.

To be clear, Mathis's studies did not address issues related to the assessment of students' written argumentation in engineering; rather, it addressed instructional moves that led to more complex engineering thinking in students' oral discourse. Other research, which has been conducted under the umbrella of argumentation regarding socio-scientific issues, likewise sheds insight on instructional moves that can lead to higher-quality oral or written argumentation when students learn about socio-scientific issues that involve engineering, such as controversies surrounding fracking or genetically modified crops. For instance, Khishfe found that it was especially important for teachers to elicit counter-arguments and to allow students to engage in familiar, relevant socio-scientific issues in order to elicit high-quality argumentation.[16] Jiménez-Aleixandre and colleagues likewise examined instructional moves that led to higher-quality argumentation regarding socio-scientific issues related to genetics. They found that students engaged in higher-quality conversations when teachers posed open-ended questions and avoided traditional teacher-dominated discourse.[17]

Assessments of Argumentation in Engineering

To demonstrate improvement in students' argumentation in engineering-related contexts, many researchers have relied on inductive, qualitative methods of analysis to determine improvements in students' oral discourse, written argumentation, or views of science. For instance, McNeill used inductive methods of qualitative analysis to identify the number of times that elementary students described evidence as a "link to an argument" and as the "results from an experiment," and she compared their views of evidence before and after an intervention on scientific argumentation.[18] Similarly, Chin and Osborne used inductive, qualitative methods to analyze middle school students' oral discourse, such as the content and function of their talk in relation to types of questions asked, as they argued about scientific phenomena.[19]

Though these methods of analysis revealed robust insights on instructional strategies that elicit complex argumentation among middle school students, we assert that domain-specific instruments are needed to assess argumentation in engineering so that researchers can determine whether instructional moves lead to improvement in students' oral or written argumentation in engineering contexts, as they are working with large data sets.

Researchers have produced relevant instruments that have been validated or that are in the process of validation. For instance, Romine, Sadler, and Kinslow produced a Quantitative Assessment of Socio-Scientific Reasoning instrument that assesses students' ability to determine complexity, perspective-taking, inquiry, and skepticism when thinking about socio-scientific issues.[20] As a second example, Osborne and colleagues developed and validated an instrument for measuring learning progressions in argumentation in science, which can trace students' developments in argumentation from constructing claims to constructing counter-claims with justifications.[6] Though this instrument can be applied to argumentation in engineering contexts, it does not include discipline-specific elements of arguments, such as weighing and justifying trade-offs based on prioritized criteria and constraints, which are features of argumentation in engineering.[21] Thus, more discipline-specific instruments are needed to assess students' argumentation in engineering.

Some existing instruments can be used to determine the quality of students' writing in engineering. Most notably, Abts and colleagues developed the *Engineering Design Process Portfolio Scoring Rubric*,[22] which includes the following two elements: "evaluation, reflection, and recommendations" and "presenting the project." These elements might be related to argumentation, in the sense that students are expected to present the project "for the audiences and purposes intended" (p. 13). As part of this presentation, students might argue that a stakeholder should adopt this design solution rather than another potential design solution. However, argumentation is not explicitly addressed in this rubric.

Given that argumentation is explicitly recommended in the middle-grades' NGSS, specific assessment instruments are needed to evaluate the quality of middle school students' argumentation using constructs that are specific to engineering (e.g., citing criteria and constraints). The purpose of this study was therefore to analyze middle school students' engineering arguments and to determine dimension of the arguments that they used, in order to form the basis of an assessment instrument that could later be expanded and validated.

Context of the Study

We conducted this exploratory study in one middle school located in the Western United States. In this middle school, 26% of the student body was identified as Hispanic on school records, 4% were identified as Asian, 1% was identified as Black, 2% were identified as multi-racial, and the remaining students were identified as White. Ten percent of students at this school were classified as English learners. The demographics of the 69 students who participated in this study mirrored the schools' demographics. These students attended a mandatory, introductory Technology and Engineering (TE) class in which the teacher presented them with various engineering design challenges and asked them to write arguments to real audiences in which they argued on behalf of their proposed engineering design solutions.

For this study, we analyzed students' arguments produced in relation to a rocket challenge. To introduce the challenge, students acted in a skit in which an aerospace engineer, portrayed by a student, met with executive members of a cube satellite company, also portrayed by students. The cube satellite company explained that they wanted to launch cube satellites above their region to better measure and predict air pollution. As part of this skit, people at the cube satellite company explained that they wanted the aerospace engineer to design a small rocket to launch their small cubes. They outlined several criteria and constraints they would like for the rocket meet, such as the ability to launch 15 or more cube satellites, to deliver the satellites safely without jiggling them, and to be made of available materials (placed on the table in front of the classroom). Acting as aerospace engineers, the students' challenge was to weight model rockets by placing the cube satellites in such a way that the satellites did not jiggle, that the rocket would go a minimum of 120 feet, and that the rockets carried a minimum of 15 cubes representing cube satellites. Students read about the science of weighting rockets, with a focus on principles such as *center of pressure* and *center of mass*. They then participated in and took notes on rounds of iterative testing related to different rocket designs, some previously made by the teacher, and some made by students. In the end they wrote an argument on behalf of their particular rocket design based on the rounds of testing and the notes they took during the testing. In this argument, they tried to convince the executives of the satellite company to adopt their rocket design as opposed to other rocket designs. Their argument was shared with an engineer who wrote responses back to each of the students.

Methodology

We collected 69 student essays in response to the rocket challenge. These essays were collected from students in multiple classes who participated in the rocket challenge. We collected essays from all students who returned their Institutional Review Board (IRB) consent forms. We conducted a content analysis in which we inductively looked for patterns across student essays. When we noticed that these patterns appeared, we assigned a code to them. The following example will illustrate our coding process. We noticed that several students wrote sentences such as the following: "It [my rocket] traveled 120 feet with a payload of 15 cube satellites" and "My rocket is very stable and will not jiggle your valuable satellites." We coded these sentences as relating to the category of "Design Requirements" because the students explicitly referred back to design requirements, or criteria and constraints, that were outlined in the skit by the CEO of the cube satellite company.

Our inductive analysis indicated that the students' arguments centered around four different categories: Testing, Science and Mathematics, Design Requirements, and Weighing Alternative Design Solutions. While developing codes to describe students' essays, we concurrently sought to develop "levels" that described progressions in the complexity for students' design thinking. For example, in the category of Design Requirements (mentioned above) we coded "uses stated criteria or constraints to justify the design" as the least complex level of engineering design thinking. Other students exhibited inferential thinking in the sense that they identified implicit criteria and constraints that were not specified by the CEO of the satellite company, such as the feature that the rocket might be reusable, and not destruct upon impact with the ground, to save on costs. We thought this type of thinking was more sophisticated because it involved inferential reasoning that required students to project desirable characteristics beyond those explicitly stated by their client. Thus, we developed the code "refers to additional desirable characteristics beyond meeting basic stated criteria and constraints to justify the design" as one level above "uses stated criteria or constraints to justify the design."

We divided the data into units, separated by sentences. We gave each unit one or more codes in separate categories, but we only assigned one code for levels within those categories. For example, consider the sentence: “We put the payload in the nosecone so the center of pressure would work in our favor we had tested it as a prototype.” We coded this sentence as appearing in two separate categories: *Testing* and *Science and Mathematics*. This sentence received two codes: “Testing: refers to tests to justify the design” and “Science and Mathematics: uses scientific or mathematical reasoning to justify the design.” As indicated by Table 1, these codes were assigned to the least complex applications of *Testing* and *Science and Mathematics*. Consequently, this sentence was coded at being on Level One in both categories. Two coders coded the entire data set and achieved over 85% agreement in codes, an indication that they were reliable. Table 1 illustrates the final codes that we developed in each of the four categories, and it indicates the number of times that these codes appeared in the data set.

Table 1

Argumentation Coding Results for Rocket Project

	Number
Level One	
Testing: Refers to one test to justify the design	51
Science and Mathematics: Uses scientific or mathematical reasoning to justify the design	68
Design Requirements: Uses stated criteria or constraints to justify the design	118
Weighing Alternative Solutions: Refers to alternative design solutions or solution elements	11
Level Two	
Testing: Refers to multiple tests to justify the design	0
Science and Mathematics: Connects scientific or mathematical reasoning to criteria and constraints to justify the design	13
Design Requirements: Refers to additional desirable characteristics beyond meeting basic stated criteria and constraints to justify the design	23
Weighing Alternative Solutions: Explains why one solution element is better than another possible solution element (e.g., why triangular fins are better than square fins)	6
Level Three	
Testing: Compares and contrasts results from multiple tests to justify the design	1
Science and Mathematics: Connects scientific or mathematical reasoning to outcomes of tests and to criteria and constraints to justify the design	1
Design Requirements: Connects results from tests to implicit or explicit criteria and constraints to justify the design	13
Weighing Alternative Solutions: Explains why multiple solution elements of proposed design are better than multiple solution elements of another proposed design	2
Level Four	
Design Requirements: Prioritizes criteria and constraints	1

Level Five **Design Requirements**: Use prioritized criteria and constraints to justify trade-offs	1

Findings

This study resulted in three major findings. First, students were generally able to participate in Level One argumentation in the categories of Testing, Science and Mathematics, and Design Requirements. Second, some students engaged in Level One argumentation in the category of Weighing Alternative Solutions and Level Two argumentation in the categories of Weighing Alternative Solutions, Science and Mathematics, and Design Requirements. Third, students were primarily focused on their own rockets and the positive features of their rockets without considering counter-arguments in relation to other proposed design solutions. In the following section, we elaborate on these findings in more detail and provide examples from student essays to highlight each finding.

Finding One: Most students were able to participate in level one argumentation in the three categories of Testing, Science and Mathematics, and Design Requirements. In fact, of all of the sentences within the essays that were coded, 78.2% belonged to these categories. Some examples of these arguments encountered in the student essays are as follows:

Level 1

Testing: refers to one test to justify the design.

"The rockets have never failed a test."

Science and Mathematics: uses scientific or mathematical reasoning to justify the design.

"As you can see from the picture below, my rocket consist of three evenly spaced fins at the bottom of the rocket witch direct the from downwards and moves the center of pressure closer to the base. Also put 15 cubes at the top of the rocket to move the center of mass upward. Because the center of mass is higher than the center of pressure, my rocket is stable."

Design Requirements: Uses stated criteria or constraints to justify the design.

"My rocket will carry your payload safely into space. My rocket is also stable, in other words it will not jiggle move or drop your satellites. It also is made of all the required materials, paper and tape."

These data illustrate that students participated in entry-level discussions or engineering design. Of these three categories, Design Requirements was most prominent at nearly double the other two. Students used information gained through testing, reading, and meeting the potential customer's needs to justify the design of their rocket.

Finding Two: Although at a lesser rate than the coded sentences of essays in Finding One, some students engaged in argumentation in the following: level one and level two Weighing Alternate

Solutions, level two Science and Mathematics, and level two and three Design Requirements. These categories contain the additional 21.8% of coded sentences from student essays. Some examples of these arguments are shown as follows:

Level 1

Weighing Alternative Solutions: Refers to alternative design solutions or solution elements.

"The other rockets may have traveled farther, but they were not very stable during their flight."

Level 2

Science and Mathematics: Connects scientific or mathematical reasoning to criteria and constraints to justify the design.

"Because the center of mass is higher than the center of presser my rocket is stable and gives your presious satilights a nice smooth ride."

Design Requirements: Refers to additional desirable characteristics beyond meeting basic stated criteria and constraints to justify the design.

"It carried 15 cube satellites, did not juggle or fall apart during its flight, and traveled more than your required distance."

Weighing Alternative Solutions: Explains why one solution element is better than another possible solution element.

"Even though my rocket didn't go as far as the others did but they all carried less than 25 rockets so I will be able to save your money."

Level 3

Design Requirements: Connects results from tests to implicit or explicit criteria and constraints to justify the design.

"I made some test on the prototype and it met all the criteria."

These examples show that, although it occurred less frequently, some students were able to consider the connections between tests, science and mathematics, and design requirements, thus strengthening their argument in favor of their design as compared to the arguments offered in Finding One.

Finding Three: Results show that students were primarily focused on their own rockets and the positive features of their rockets. There was little engagement in weighing of alternative solutions, considering trade-offs, or prioritizing criteria and constraints. There could be many factors that explain why students did not prioritize criteria and constraints in the process of weighing trade-offs. Instructional design and delivery, lack of student experience in engaging in argumentation, and time available to concentrate on this unit (which was about 2.5 weeks in duration) could all be factors that limited students' ability to engage in these sophisticated forms of argumentation. Overall, this finding does show that although most students engaged in basic engineering argumentation, some types of complex engineering argumentation were more elusive.

Limitations

This study was limited in the sense that it was conducted in one middle school with one teacher in relation to one engineering design challenge. Although this exploratory study produced promising results, such as content related to a field-tested assessment tool that can be used to categorize and code students' written argumentation in relation to engineering-specific domains, future research can further develop and refine this assessment tool through implementation in other middle school classes with more diverse students. In addition, this study is limited in that it did not specifically measure the performance of English Language Learners (ELLs) compared to students who were not English learners. One additional limitation is that the students were asked to submit individual papers. Had the students worked as groups to create a group response comparing all rockets in the group, we would expect to see more levels and depth of argumentation.

Implications

This study resulted in a content analysis, offered in Table 1, that can be used to create a preliminary assessment tool, which can evaluate students' engineering arguments along four domains. This type of tool can contribute significantly to research and practice by providing teachers and researchers with a vehicle for evaluating their students' arguments in relation to engineering-specific domains of thinking, such as Testing and Design Requirements (criteria and constraints). Future studies can expand this assessment instrument by testing it in other middle school classrooms, and they can validate later iterations of this instrument.

References

[1] Manz, E. (2015). Representing student argumentation as functionally emergent from scientific activity. *Review of Educational Research, 85*(4), 553-590.

[2] Sampson, V., & Blanchard, M. R. (2012). Science teachers and scientific argumentation: Trends in views and practice. *Journal of Research in Science Teaching, 49*(9), 1122-1148.

[3] Ryu, S., & Sandoval, W. A. (2012). Improvement to elementary children's epistemic understanding from sustained argumentation. *Science Education, 96*, 488-526.

[4] Venville, G. J., & Dawson, V. M. (2010). The impact of a classroom intervention on Grade 10 students' argumentation skills, informal reasoning, and conceptual understanding of science. *Journal of Research in Science Teaching, 47*(8), 952-957.

[5] NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states.* Washington, DC: The National Academies Press.

[6] Osborne, J. F., Henderson, J. B., MacPherson, A., Szu, E., Wild, A., & Yao, S.-Y. (2016). The development and validation of a learning progression for argumentation in science. *Journal of Research in Science Teaching, 53*(6), 821-846.

[7] Yerrick, R. K. (2000). Lower track science students' argumentation and open inquiry instruction. *Journal of Research in Science Teacher, 37*(8), 807-838.

[8] Zohar, A., & Nemet, F. (2002). Fostering students' knowledge and argumentation skills through dilemmas in human genetics. *Journal of Research in Science Teaching, 39*(1), 35-62.

[9] Toulmin, S. (1958). *The uses of argument.* Cambridge, UK: Cambridge University Press.

[10] Erduran, S., Simon, S., & Osborne, J. (2004). TAPping into argumentation: Developments in the application of Toulmin's argument pattern for studying science discourse. *Science Education*, *88,* 915-933.

[11] Sampson, V., & Clark, D. B. (2008). Assessment of the ways students generate arguments in science education: Current perspectives and recommendations for future directions. *Science Education, 92,* 447-472.

[12] Goldman, S. R., Britt, M. A., Brown, W., Cribb, G., George, M., Greenleaf, C., Lee, C. D., Shanahan, C., & Project READI. (2016). Disciplinary literacies and learning to read for understanding: A conceptual framework for disciplinary literacy. *Educational Psychologist*, *51*(2), 219-246.

[13] Moje, E. B. (2008). Foregrounding the disciplines in secondary literacy teaching and learning: A call for change. *Journal of Adolescent & Adult Literacy, 52*(2), 96–107.

[14] Mathis, C. A., Siverling, E. A., Glancy, A. W., Guzey, S. S., & Moore, T. J. (2016). Students' use of evidence-based reasoning in K-12 engineering: A case study. *Conference Proceedings of the American Society for Engineering Education,* New Orleans, LA.

[15] Mathis, C. A., Siverling, E. A., Glancy, A. W., & Moore, T. J. (2015). Teachers' use of argumentation in the development of integrated STEM curricula. *Conference Proceedings of the American Society for Engineering Education,* Seattle WA.

[16] Khishfe, R. (2012). Relationship between nature of science understandings and argumentation skills: A role for counterargument and contextual factors. *Journal of Research in Science Teaching, 49*(4), 48-514.

[17] Jiménez-Aleixandre, M.-P., Bugallo Rodríguez, A., & Duschl, R. A. (2000). " Doing the lesson" or "doing science": Argument in high school genetics. *Science Education, 84,* 757–792.

[18] McNeill, K. L. (2011). Elementary students' views of explanation, argumentation, and evidence, and their abilities to construct arguments over the school year. *Journal of Research in Science Teaching*, *48*(7), 793-823.

[19] Chin, C., & Osborne, J. (2010). Supporting argumentation through students' questions: Case studies in science classrooms. *Journal of the Learning Sciences, 19*(2), 230-284.

[20] Romine, W. L., Sadler, T. D., & Kinslow, A. T. (2016). Assessment of scientific literacy: Development and validation of the Quantitative Assessment of Socio-Scientific Reasoning (QuASSR). *Journal of Research in Science Teaching, 54*(2), 274-295.

[21] Wilson-Lopez, A., & Minichiello, A. (in press). Disciplinary literacy in engineering. *Journal of Adolescent & Adult Literacy.*

[22] Abts, L. (2011). *Engineering design process portfolio scoring rubric.* Retrieved from: http://teams.mspnet.org/media/data/EDPPSR.pdf?media_000000008449.pdfv