Board 116: Investigating Optimization as a Practice in Middle School Engineering

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Gabe Knowles joined the Center for Science and the Schools at Penn State University as a STEM Education Outreach Specialist in 2018. His role with CSATS is to collaborate with Penn State University scientists, engineers, and graduate students to develop and deliver professional development opportunities for K-12 teachers. Gabe's primary focus of work is creating professional development opportunities for elementary teachers related to STEM education.

Gabe has extensive experience in public education having taught for 16 years in the classroom. During this time he taught math and science classes in grades 4, 5, and 6 as well as teaching middle school technology courses for grades 6-8. He also has taught all subjects in an inclusion classroom for several years. Gabe facilitated his classroom by engaging his students in an interdisciplinary thematic format as well as using project-based and place-based education strategies. He also has extensive experience in environmental stewardship and education outreach opportunities with the National Park Service, such as creating STEM curriculum and education workshops for Grand Teton and Black Canyon of the Gunnison National Parks.

Prior to his teaching career, Gabe worked in the field of wildlife ecology with the United States Geological Survey-Biological Resources Division at the Las Vegas Field Station in southern Nevada. His primary role was a field technician responsible for supervising field crews conducting research on several studies of the desert tortoise in the Mojave Desert. This position had Gabe working remotely across rugged desert terrain in Arizona, California, Nevada, and Utah.

Gabe has received several honors and recognition for his continued work, such as an Americorps Education Award, Teacher-Ranger-Teacher Award from the National Park Service, President's Volunteer Service Award from George W. Bush, and the Exceptional People In Community Schools Award from the Michigan Education Association. His continued work in education, stewardship, and outreach have impacted children of all ages, including adults and professionals working in an array of fields.

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Taylor received his B.S. degree in Physics from Brigham Young University, after which he worked for 5 years as a semiconductor engineer for Micron Technology in Boise, ID, specializing in numerical and computational data analysis. During this time, he also volunteered extensively with the educational arm of the Micron Foundation, bringing inquiry-based STEM outreach lessons to K-12 classrooms throughout the Boise area and serving as a career mentor to high school students interested in pursuing engineering as a career. Taylor's role at CSATS focuses on interfacing with science and engineering research faculty to develop and implement K-12 teacher professional development.

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Investigating Optimization as a Practice in a Middle School Engineering Class (Work In Progress)

Abstract

This work in progress paper describes a pilot study intended to better understand the ways students and teachers in a middle school engineering class iteratively optimize a multi-objective problem. Recent reforms in STEM education have placed an emphasis on engaging K-12 students in the knowledge-building practices of professionals as a way to teach and apply content, but so far few have looked closely at classrooms engaged in these practices. An ethnographic perspective was used to closely observe the talk and actions of three groups of eighth-grade students from a low-income rural school district and their teacher as they attempted to minimize cost, mass, and deflection of a truss cantilever using two computer-based tools. Methods of interactional ethnography were used to analyze the ways in which they took risks to test the boundaries of the structure and balanced tradeoffs while still producing a physical prototype that could hold a 1.5 kg mass. Preliminary results suggest that when supported by their teacher, students became increasingly more comfortable with taking risks and pushing the limits of the structure in low-stakes situations. Additionally, we found that students were able to use a variety of approaches to strategically remove structural members, including applying scientific knowledge, and were able to appropriately compare multiple models to inform the design of their physical prototype. To our knowledge, this is the first study to investigate optimization explicitly as a practice in a precollege context, and it contributes to the knowledge base of our understanding of how students and teachers do engineering and how engineering educators can promote improved curriculum and pedagogy in this area.

Introduction

STEM educators are now placing an emphasis on the importance of teaching students content through engagement in *habits of mind* [1,2] or the practices of disciplinary experts [3,4,5,6]. However, this presents significant challenges to K-12 educators, most of whom have limited experience with doing authentic science or engineering and many of whom are not comfortable with teaching units without normative answers [2]. Engineering in K-12 settings has become more and more common since the release of the *Next Generation Science Standards* (NGSS) [7] and since state education departments began developing standards requiring engineering content and practices [8]. Since curricular materials and professional development workshops are becoming available for these teachers that lack engineering experience, it is timely to investigate the ways in which teachers and students collectively engineer in the classroom.

The *Framework for K-12 Science Education* [4], the document that NGSS is based upon, lists only two distinctions between the practices used by disciplinary experts in science and engineering. However, some have argued that the epistemic practices of engineering are significantly different from those used to create knowledge in science, and that STEM educators should take advantage of these differences rather than focusing on the similarities [9]. Then, Cunningham and Kelly [10] synthesized from the literature on professional engineering a list of epistemic practices that are potentially useful in the K-12 classroom. Among that list, several are relevant to the study described in this report: (1) making tradeoffs between criteria and constraints; (2) applying science knowledge to problem solving; (3) assessing implications of solutions; and, (4) building and using models.

The disciplinary practices of engineers can be experienced by K-12 teachers through a variety of professional development opportunities. National Science Foundation requires researchers to explicitly state the *broader impacts* of the funding they receive to do research, and often engineers choose to host teacher workshops to reach teachers that serve in districts with high percentages of students that are typically underrepresented in STEM fields. This study was born out of a teacher workshop developed as a collaboration between a university-based education center and a civil engineering faculty member whose work focuses on optimization. We argue that optimizing a multivariate problem is an important practice in engineering that is conceptually attainable for K-12 students, but is typically buried in the practice of iteration and is rarely the focus of classroom activity [2]. For these reasons, we piloted a small study to look closely at how a teacher and his class of eighth grade students from a rural school in the Northeast attempted to optimize a truss structure.

Description of the Optimization Project

Many freely available K-12 engineering lesson plans instruct students to design and build a structure with a constrained amount of material that is either as strong as possible [11] or as tall as possible while able to hold a weight [12]. However, neither of these goals resemble the work of engineers [13]. Builds like this would be wasteful in terms of resources, so many civil engineering firms employ engineers specifically to minimize material, time, and cost while still adhering to the specifications of the structure.

The goal for students in this activity was to minimize cost, weight, and deflection of a truss cantilever when a 1.5 kg mass is applied at a distance of 2 feet from the base. The structures were all made out Micro K'Nex using blue (9.5 cm) and purple (14.5 cm) rods and gray connectors. All student groups were given a "ground structure" to start. It was the most rigid structure possible with the given specifications, but was the heaviest and most costly. The students were charged with optimizing the ground structure to balance the tradeoffs of cost, weight, and deflection when holding the 1.5 kg mass (Figure 1).

In order to analyze trusses to identify members and nodes that were able to be removed, students first had to understand the importance of triangles in the stability of trusses. A one-day lesson was taught to the students where they used an inquiry-based approach to identifying that triangles are the only stable polygon, and that other polygons can be made stable by adding braces that subdivide the structure into triangles. Through this investigation, they deduced that the relationship between the joints (j) and the members (m) of stable structures is 2j-3=m. This is the equation used in evaluating static determinacy, and this formula must be met to use the method of joints to evaluate the individual forces on the members of the truss.

Figure 1 - A photo of the ground structure attached to the base with a 1.5 kg load applied at a distance of 24 inches from the base

Rather than doing physical testing of the modifications, students were encouraged to model multiple solutions, so they were taught how to use the freely available software, Mastan 2, a program that is able to perform linear and nonlinear analyses for demonstration, solving problems, and performing analysis and design studies. We created two files, one with one face of the ground structure and the other a simpler version for students to practice with. Both were programmed to include plastic the size of micro K'nex by inputting the Young's modulus and Poisson's ratio as the material properties. Only one face of the structure was used in the software for simplification, but the load was decreased accordingly. Through multiple tests, the simulated deflection matched well with the actual deflection. Students learned how to use four of the outputs from the program (Table 1).

Type of analysis	Description and use
Axial forces	Gives a graphical representation of the amount of force on each member. Students used this to visually identify potential targets for removal and to identify patterns of force distribution within the structure
Element report	Gives a numerical report of the forces on each member. Students used this to identify zero- and low-force members as potential targets for removal.
Deflected shape	Gives a predicted shape of a structure under the given load
Node displacement	Predicts the distance a node will deflect. Students used this analysis to predict the amount of deflection of the node where the load is applied to assess deflection of the structure.

Table 1-A description of the four analyses students learned how to use in the tutorial

The other tool used by the students was called the Decision Criteria Sheet (DCS) and was developed to help students evaluate the modifications made in each iteration. This Microsoft Excel spreadsheet enabled the students to enter the number of elements and nodes used in each iteration as well as the predicted deflection. Embedded into the sheet are formulas that take those inputs to calculate cost ($1 per linear centimeter of elements and $5 per node) and the mass of the structure. It also calculates a composite score by multiplying cost, mass and deflection by an importance factor so the variables were more equally weighted[1]. This score gave feedback to the students to compare iterations, with a lower score preferable to higher ones. Removing members decreases both cost and mass, but increased deflections raise the score.

Materials were purchased to allow teachers interested in using this lesson in their class. The kit contains the necessary K'Nex, a base to attach the physical prototype for testing, masses, instructions, and the electronic files. Detailed instructions are also included for aiding implementation[2].

This lesson took a total of nine 40-minute class periods to (1) learn about the importance of triangles for stability (one class period); (2) learn how to use the analysis software and practice on a simple truss structure similar to the one used in the activity (two class periods); (3) work in teams of three to iteratively optimize the ground structure through modeling and analysis

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[1] For example, costs were in the thousands of dollars, but deflections were in tenths of inches, so deflection was multiplied by a factor of 3,000.

[2] All files used can be obtained by contacting the lead author.

and then make modifications to a physical prototype (five class periods); and, (4) conduct two rounds of physical testing and scoring of the physical prototype (one class period).

Participants

This study was a pilot test in one eighth-grade class taking *Introduction to Engineering* in a rural school in the Northeast United States. The school is the only middle school in the district and has approximately 110 students per grade. The student population is 98% Caucasian of which 54% receive free or reduced lunch prices, a proxy for low socioeconomics. A majority of the students also represent potential first-generation college students. All nine students in the class participated in the study.

The teacher attended a one-day workshop in May of 2018 about this topic sponsored by a National Science Foundation grant (# CMI-1351591). Teachers in this workshop engaged in the same activity described above. Mr. Pfeuffer (pseudonym) is certified in technology education and has fifteen years of teaching experience, fourteen of those years in his current placement. He was the first teacher to express interest in implementing the lesson in his class, which is why this was chosen as the site for a pilot study.

Theoretical Framework

This study is guided by empirical work on engineering practices, and it considers the materials and tools used in engineering as actors in the discourse that is used by the participants to accomplish their work. Because sociocultural work relies on discourse, interactional ethnography can used to better understand how students and teachers collectively participate. A more detailed description of this theoretical framework can be found in [14]. This framework guided the research, including the questions asked, methodology used, and analytic decisions we made.

Research Questions

To investigate optimization in our specific context, we set out to answer the following question:

1. How do students and their teacher collectively optimize a multi-objective design through modeling and analysis?
    A. What role does risk taking play in the process and in presenting their final prototype?
    B. What knowledge, tools, and approaches do they use to improve their designs?

Research Methods

Our study takes an ethnographic perspective that is informed by discourse analysis to investigate precollege engineering because classroom activity is sociocultural in nature and relies heavily on language [15]. Interpretation of talk and action in these setting requires knowledge above and beyond that needed to analyze transcripts of individual interactions [16], so the lead author acted as a participant observer [17]. In this role, the researcher was able to better understand the classroom culture [18] and facilitated contextualizing the overall activity and the isolated instances making it up [19]. Polkinghorne [20] describes this as the *hermeneutic circle*. This approach to studying STEM learning can be read in greater detail in [16] and Johnson [14].

We used classroom video and student artifacts as data. Digital video recordings were used to generate event maps (time-stamped descriptive records) and word-by-word transcripts. Three video cameras were used. One was a wide angle fixed on the whole class to help us understand both the movement of the teacher and to capture work done as a whole class. Two additional cameras were fixed on groups of three students at an angle from behind them, to be able to view their computer screens. A portable microphone was placed in front of them to help us better hear their group conversations. A total of 19 hours of video was uploaded to V-note qualitative research software and the audio and video files were synched.

Consistent with our theoretical framework, the construction of the learning experience occurs when students and teachers interact within the boundaries of the classroom culture, with each of them participating as they best understand their role. These interactions occur through discourse [19], so we used interactional ethnography as a method for interpreting the interactions. Twenty-seven event maps [14, 21] were generated to record how students and teachers spent their class time. In addition, one- to two-paragraph summaries were written to maintain an audit trail [22], and to make explicit the initial reactions we had as analysts to the activity.

The research team met frequently to discuss our initial understandings of the actions, and chose to focus more closely on the element of risk-taking, both in the computer modeling as well as in the transition from computer model to the physical prototype. We also were interested in the ways the students used their understanding of the physical phenomenon of stability in structures, particularly their understanding of triangles. Third, we were interested in the ways the teacher attempted to support the students in their pursuit of optimizing the structure.

We used a constant comparative approach [23] to coding for instances of risk taking (or aversion to risk), instances where students used scientific understanding in their discourse, and for the types of interactions the teacher had with the groups. Relevant instances were transcribed word-by-word for microanalysis, but were able to be contextualized within the overall activity and culture of the class. This methodology is reliant on interpreting talk and action of the participants which is facilitated by the analysts' own experiences [18]. In other words, our analysis is clearly influenced by our own understanding of classroom work and engineering, so we deliberated set out to increase the trustworthiness through maintaining an audit trail, collaboration and peer review, and by presenting a thick description of our findings [22]. A detailed description of the research and coding methodologies can be found in Johnson [14].

Preliminary Results

Initial analyses suggest two interesting findings. First, students learned, with support of the teacher, how to take risks in trying to optimize the cantilever. Second, the students used a variety of sophisticated strategies to iteratively improve their structures which included using multiple tools for analysis and relying on scientific knowledge to make evidence-based decisions. Interestingly, as occurred in the teacher workshop held on this topic, the number of iterations, the approach to optimizing, and the final structures varied greatly between the groups. Additionally, each final tested prototype successfully supported the load without breaking.

Risk taking

At the beginning of the activity, students were generally reluctant to take risks in the form of removing many members at once. This was evident in the discourse surrounding the first analysis each group had to run on the modeling software. A first-order elastic analysis let them know if the newest iteration was stable. The groups were pleasantly surprised when they removed members to find it was still stable. But as the students got more experienced, both groups were more willing to push the boundaries. One example of this was when Randall and Maddy were discussing removing most of the elements from the top and replacing some in another region of the structure to try to decrease deflection. Randall realizes that there is little risk in this radical move because if it turns out to be unstable, they can just go back to the previous iteration (Table 2, lines 5-11).

Time	Line #	Maddy	Randall	Context clues
29:58	1 2 3	We can just remove a bunch of them from the top and add them back to this side and see if it's still stable,		Points to the upper section of the computer model
30:33	4 5 6 7 8 9 10 11		Yeah, we could try that. No. Wait. We wouldn't really be changing anything by the shape, oh, except for making it stronger. Yeah, let's just try that.	

Table 2 - Randall and Maddy discuss taking a risk by removing a large number of members

This approach to pushing the boundaries of the structure through iterative modeling was encouraged by all of the adults in the room, including two civil engineers that attended one class to observe and interact with the students. Frequently throughout the last four days of the activity, the teacher encouraged the students to "be aggressive" and to take risks in trying to improve the structure. A relevant example was when Mr. Pfeuffer was working with Lisa, Maddy, and Randall on strategies to improve. The teacher uses the term aggressive referring to taking risks and removing more than a few elements (lines 12 & 26).

Time	Line	Lisa	Maddy	Randall	Mr. Pfeuffer	Context Clues
29:08	1 2 3 4 5 6				What are we removing? I'm going to help you with one more.	Lisa is making changes to model truss as the other two students are observing Mr. Tate at the computer.
	7		13 and 28.	13 and 28.		
	8 9 10 11 12 13 14				13 and 28. That's all you wanna do? Don't you want to get any more aggressive out here with any of this?	Mr. Pfeuffer takes over Randall's computer to make changes. All three students are standing behind the teacher.

	15 16 17				We could try all this.	
	18 19		Yeah.	You could do that.		
30:09	20 21 22 23 24 25 26 27 28 29 30 31 32				“So that’s 52, 56, 57, 28, 49, and 18. Ok. SO you guys ready for that? See what happens. This is what I mean by getting aggressive. You guys have to take a look at all this, try it. Or you’re not going to have a shot at winning the bid.”	Mr. Pfeuffer is controlling the mouse of the computer and all three students are observing him.

Table 3 - The teacher encourages students to take risks

This is one poignant example of episodes that happened frequently throughout the project. The teacher put an emphasis on what he considered “aggressive” design moves, and the students gradually started to understand one of the values of computer modeling, the ability to iterate quickly with no negative repercussions for failing.

Due to the different styles and strategies used by the students, the designs evolved differently. Although we were initially concerned about convergent designs occurring since everyone started with the same ground structure, we found that in both the teacher workshop and in the classroom studied (as well as in other classes who recently did this activity), the designs varied greatly. Figure 2 depicts the variety of the approaches and results from the student groups’ progress through the activity. Group 1 made a total of 10 iterations and earned the lowest (best) score. Group 3 used 18 iterations to achieve the lowest deflection score, and Group 2 used 11 iterations to settle on their final prototype.

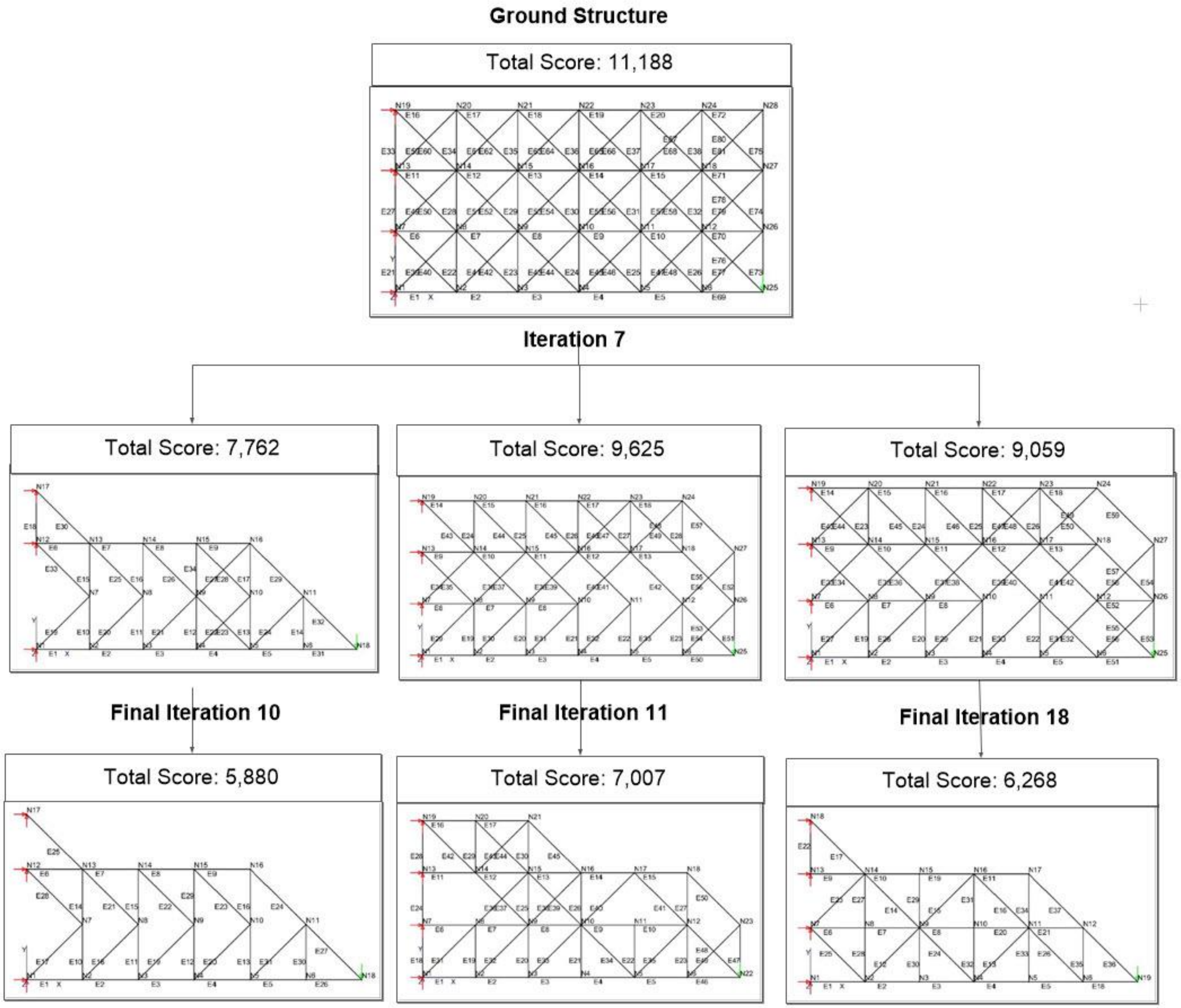

Figure 2 - This figure shows the screenshots of the students' ground structure, 7th, and last iterations of the three groups. All groups made significant improvements signified by the decreasing scores. Group 1 (left) improved the most and in the fewest iterations

Using multiple approaches

The approaches student groups took varied in interesting ways. The tools available to the students provided them with a number of options, and students used them in fairly sophisticated ways. The decision criteria spreadsheet (DCS) offered the students a tool to analyze the predicted scores of each iteration. In addition, students used the axial force diagram, the element report, node displacement prediction, and the deflected shape analysis (see Table 1) to make decisions about the elements to remove. Perhaps most interestingly, student groups used their understanding of the importance of triangles to stability to help them make decisions.

The DCS was designed to help students interpret iterations with multiple criteria as a way to balance trade-offs. They input the number of members and nodes and the predicted deflection from Mastan. A decrease in the composite score signaled an improvement; an increase was interpreted as an option that should be rejected. Not only were students able to interpret the scores as an indicator of the relative value of the prototype, they also used it as a tool to communicate with their group members.

During the tutorial, students learned four separate options for analyzing their structure. The axial force analysis was a visual representation of the relative forces on members (Figure 3). Overlaid on the diagram was an additional set of lines parallel to the elements. The closer the line was to the element, the less force is experienced, and thus was a potential target for removal. In addition, the members were labeled with the amount of force the member experienced.

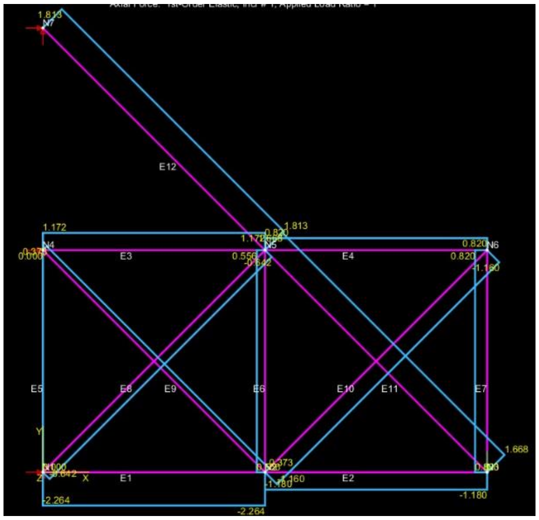

Figure 3-The axial force analysis was used by all students to identify potential elements to remove. Elements depicted close together were identified because they experience less force

Students also learned how to use another report which was a table of all the elements and the force vectors (magnitude and tension/compression). Students in each group used it less frequently than the axial force diagram. The deflected shape diagram showed them the predicted shape of their iteration. Few students used this option because it provided no quantitative data for them to use. Finally, the node displacement had to be used to input a deflection in the DCS tool. Students quickly learned to find the predicted displacement in the Y direction (vertical), and understood that the negative value referred to direction of the movement.

An important aspect of the project was the connection of the understanding of the phenomenon of structural stability. After the first several iterations, students were frequently engaged in discussion about the triangles in their trusses. In many cases, the students were cognizant of the fact that removing a low-force member was not possible because it would lack a triangular region and thus would be unstable. In other cases, students were able to identify this as a reason an iteration was deemed unstable by the computer software. All groups had multiple conversations both among themselves and with the teacher. One poignant example can be seen in the discussion between Laura, Rachel and Ernie, a local engineer who came to observe the activity. Their conversation uses the axial force diagram as a communication tool, representing the physical prototype. It is clear from this interaction as well as others that the students are able to use this tool to consider their next steps and to analyze previous iterations in more deeply than reading the composite score. Maddy talks to Ernie about adding members back to decrease the deflection (Table 4).

The teacher facilitated this approach through his frequent reference to triangles. Especially interesting was a discussion between Larry, Rachel and Mr. Pfeuffer. They were discussing why their latest iteration was unstable.

Time	Line	Laura	Maddy	Ernie (guest engineer)	Contextual Clues
40:46	1 2 3			Are you going to take more pieces out now?	
	4 5 6		I am open to it if we can find the right pieces		
	7 8 9			What does your model look like now if you run that?	
	10 11	No, do an analysis first			
	12		Yah		
	13 14	What is your displacement now			
	15 16		[inaudible answer] It didn't fix that		
	17			Fix what?	
	18 19 20 21		It kind of looks the same here. We added the X back in, but it didn't help that.		Referring to adding triangles back in
	22 23			You were kind of hoping it would stay up right?	
	24		Yah		
	25			Which one was it again?	
	26 27 28		E62. I think we should add those back in, but I don't know		
	29			Which ones?	
	30		Those 3 down like that		
	31 32 33 34 35 36			I think you are right, because what is happening is the bottom is kind of pulling away. If you support it from the top, it will pull back up.	Ernie points at the screen and then uses his hands to emphasize the direction
	37 38 39 40		Should we add just these two? Or should we add that one as well?		Points at areas to add back members to increase strength
42:42	41 42 43 44 45 46 47 48 49			I think if you put it back here, you will get more I think the closer it is, because it is holding it back here. Because if it is weaker out here, and you put it out there it will just hang down again. I would try back here.	Ernie again uses the diagram to point to specific elements to help answer Maddy's questions

Table 4 - Group two discusses their improvements with an engineer visiting the class

The teacher facilitated this approach through his frequent reference to triangles. Especially interesting was a discussion between Larry, Rachel, and Mr. Pfeuffer. They were discussing why their latest iteration was unstable. Rachel points to some structural elements that they tried to remove but resulted in unstable structures (lines 5-7). The teacher recognizes that the elements they tried to remove made the structure unstable because it became statically indeterminate, and had them recognize this by pointing out regions that are not made of triangles. To emphasize this point to the whole class, he gets the class' attention to remind them of the point of the first activity, that triangles are the only stable polygon.

Time	Line	Larry	Rachel	Mr. Pfeuffer	Context clues
27:24	1 2 3 4	We don't know what to do. We've taken a lot off, but can't find any more			
	5 6 7		Yeah, we tried these, but they were unstable		Points at screen to three elements
	8 9 10	We don't know if we should take any others off			
	11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37			Why would that have been unstable? Let's look at that first. You can see there's not much weight on those elements, but what would have made it unstable? Think back to the first lesson. What was it about? Last Monday. What was it about? Class, go back to the first lesson last Monday when we worked with the Legos. What was the purpose of that lesson? Thank you So when you removed that one, was it a triangle?	Turns to class A student from another group off camera says, "Triangles" Turns back to the group Points at screen
	38	Oh. No.			

Table 5 - Mr. Pfeuffer reminds Group 1 and the class that their truss must be made of triangles or it will be unstable.

The groups became more skilled at identifying structural members to remove and also which ones to avoid because removing them would create instability. In fact, Larry and Rachel were confused when it appeared their structure was made of all triangles but the analysis showed instability. Both the teacher and the researcher were also unable to recognize the area causing the instability. Table 6 shows a conversation where Mr. Pfeuffer and the researcher try to help the students. The teacher agrees that the member they are trying to remove is not bearing much weight and should be removed (line 6-7) and the researcher also did not know why (lines 81-84).

Time	Line	Larry	Rachel	Mr. Pfeuffer	Researcher	Context Clues
14:34	1 2 3 4 5 6 7 8 9 10			So it’s unstable. So put those back in. I’m curious as to why that would be? Because, they were showing no mass bearing at all.		Mr. Pfeuffer turns to the researcher and begins to ask him questions about the problem that the students are having.
	11				Uh huh.	
	12 13 14 15 16 17 18 19 20		I need to add it. I don’t even remember.	It went right to unstable. Come over here, I’ll tell you.		Rachel hits her head with her hand with disappointment. Rachel gets up from her chair, but quickly sits down after Mr. Pfeuffer says he will help.
	21 22 23		Is it like this?	Define. An element. Draw it in.		Mr. Pfeuffer begins giving Rachel directions.
	24 25 26			Uh-hum. Hit apply. Do another one.		
	27 28 29 30 31 32 33 34 35 36 37 38 39		Do I do it over again? This one?	Yes. Yeah. You need to put it back in where it was. So it’s the one coming up on angle there, Yup. That one. Up at an angle. Straight up to at eleven. Yup.	Not there.	

	40 41 42 43 44 45 46 47 48 49 50 51 52			Now you go into properties. Find section, wait, hold on. Attach section. Click on those and hit apply. Now you have to go into properties to find material.	You can do both of them.	
	52 53 54 55 56 57 58 59 60 61 62			Go ahead and maybe click on it. So, you are going to run that test, and I want the researcher to look at it.	You can just touch it. Attach.	Researcher takes over mouse from Rachel. Larry sets physical model on the desk.
	63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84	Go to results.	What, with this? So, what are these again?	The test you just ran, that showed why I gave the opinion on what I did. Go to analysis. And, you had, um, yeah, that one. They are showing no weight bearing. What's your opinion on that?	Go to analysis. Yup. Yup. Um, I honestly don't know. I see what you are saying.	Rachel grabs model responding to Mr. Pfeuffer. Mr. Pfeuffer responds by pointing to computer screen. Researcher walks over and sits next to Rachel.

Table 6 - Group one and the teacher try to determine the cause of an unstable analysis.

After class, the teacher and researcher realized an area of the structure appeared to be a triangle, but was actually made up of four members. This is an important and interesting example that will likely happen in classes that do this type of activity. Figure 4 illustrates the problem. Four members form a three-sided structure; however, the node in the middle on the bottom makes this region unstable, because the region is formed by four members, not three.

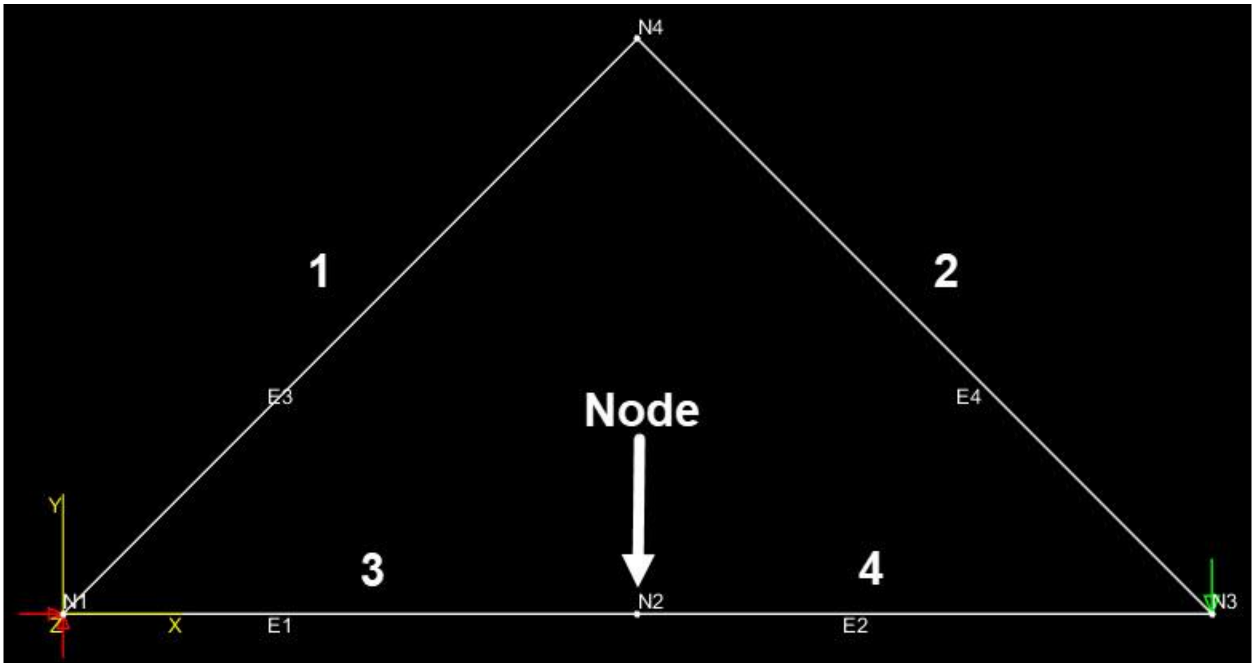

Figure 4 - A three-sided shape made of four members is not stable, but appears to be a triangle. This problem confused students, teachers, and the researchers!

The next day, the researcher met with the group to help them understand why removing the member made the cantilever unstable (Table 7). Even pointing it out to them, they initially did not recognize it was a quadrilateral (lines 5 and 10). However, they soon understood (line 13 and 19) and were able to show their classmates.

Time	Line	Larry	Rachel	Researcher	Context clues
4:20	1 2 3			Even though that looks like a triangle, how many sides are on that?	Mr. Pfeuffer points to computer screen while asking question.
	5 6 7	Three. Which one?			Mr. Pfeuffer traces an outline of a shape on the screen with his finger.
	10 11 12	Three.	Three.	Yeah. But, the problem is there are two separate segments here.	
4:48	13 14 15 16 17 18 19	Oh!	Oh! Ok.	So, it's like a quadrilateral, but it has two line segments intersecting. That's why that unstable, even though it looks like a triangle, it still has four sides.	

Discussion and Implications

The students and the teacher in this class used a variety of tools and approaches to improve their structures. Using an interactional ethnographic approach to understanding classroom activity as promoted by Kelly & Green [16] allowed us to look closely at what happens in the small groups that engineering projects typically happen in precollege settings. In these K-12 settings, engineering failure is often conflated with academic failure [23]. However, in this activity, the students gained the confidence to test the boundaries of their structures as they realized a failed iteration could be rejected. In the framework on failure and improvement described by Johnson [13], this would be called "low-stakes failure" because the failure happens in a small-group setting and there is time to make modifications prior to the high-stakes test done at the front of the class. Therefore, students were able to test the boundaries of the system without the fear of failing publicly. Modeling in this way allowed each group to significantly improve their structures while still accomplishing the goal of supporting a 1.5 kg load placed 2 feet from the base.

Additionally, the middle school students in this study demonstrated to the research team their ability to use a variety of analyses to guide their optimization process. But rather than solely finding low-force members and removing them, all three groups used their understanding of how triangles affect stability when making their decisions. But in addition to applying scientific understanding to the engineering problem, the students used a variety of approaches to identifying members for removal or replacement, and spoke strategically about their next iterations.

Based on our pilot study, the role of the teacher in supporting students taking risks and using multiple approaches and tools is essential. However, since few teachers have experience in the practices of engineers, we promote teacher professional development workshops that engage teachers in the same types of activities their students will. We plan to expand on this work, by conducting a study following teachers through their experience in professional development and then looking for connections between their experiences in the workshop and their implementation of the activity in the classroom.

Although this was a pilot study done in only one small classroom, we argue that this investigation of optimization will be interesting to some in precollege engineering education because optimization is a *habit of mind* [1,2] and a *practice* that is used by professional engineers [4]. By engaging students in optimization activities like the one described in this paper, they will be given the opportunity to utilize creativity and problem solving while applying relevant science and math content [10] to iteratively improve their design. We are unaware of other studies of this kind, but we feel this offers an interesting and timely opportunity for researchers in engineering education to support improvement in precollege engineering teaching and learning.

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