121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #9224

Teachers' Attempts Assessing Middle School Engineering Design Work

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Abstract

Engineering has made its way into many K-12 classrooms over the past ten years. Teachers are asked to teach engineering through engaging engineering design projects with little (i.e., daylong to weeklong professional development workshops) to no preparation or background knowledge in engineering. Even with limited preparation many teachers do quite well implementing exciting engineering activities leading to high quality final prototypes from their students. However, assessment remains to be an area that is under-emphasized in professional development activities. Assessing the students’ final engineering work can pose many challenges as the work is often completed in teams, takes many differing forms across the class, and does not consist of “right” answers. However, professional development opportunities often focus on the seemingly more pressing issues of providing teachers the necessary background engineering knowledge and specific curriculum knowledge such that teachers can begin teaching engineering.

The study presented in this paper investigated six middle school teachers as they embarked on teaching an approximately 15-hour engineering design curriculum following a one-week professional development workshop. The goal of the study was to understand the various types of teacher knowledge the teachers used and developed over the course of implementing and engineering design curriculum. The data presented comes from one-on-one interviews (each approximately 20 minutes in length) with the teachers where they were asked to talk about designing a rubric for their students’ final projects. They were then asked to apply this rubric to a few sample projects from their class. The data reveal common themes or features the teachers focused on in their design of the rubric. The teachers initially focused on team and process-oriented features (e.g., teamwork, organization, steps of design process) and how well the final solution worked. The teachers tended to focus less on knowledge-oriented features relating to the application of STEM (science, technology, engineering, and mathematics) principles as they developed their rubrics. As the teachers applied their newly developed rubrics to their students’ final projects, they focused on surface features of teamwork and process and struggled to identify the specific technical accomplishments of the teams’ work. The conclusion includes implications and future research work related to developing teachers’ engineering project assessment skills and knowledge.

Introduction

Consider the exchange below from an interview of Frieda, an eighth grade science teacher, discussing her strategy for assessing her students’ engineering design projects with the author/researcher. Frieda had recently completed a 15-hour unit on the engineering design process (EDP) where students engaged in various EDP strategies to design, build, and test a LEGO-based assistive device. The researcher presented a few of the student teams’ final prototypes and asked her to describe how she would go about assessing her students’ final project work.

Interviewer: I brought some pictures of the students' final projects and want you to assess them. Do you use rubrics to assess students work?

Frieda: I do. As a matter of fact I have a rubric for the scientific method.

Interviewer: If you were to assess final projects for your students what are the different categories you would have. You can have a rating if you want or you can go 0 to 6.

Frieda: I usually do a points system so if I were to look at this I would use the EDP [engineering design process] and put points with every step to see if they did this step or that step. If they did every step, then probably everything would be sufficient and it wouldn't be falling apart and [they would know] exactly what their creation is. Probably it would be a point system. So I would probably put ten, ten or something like that on a scale of 100.

Interviewer: So why don't we do that for these then.

Frieda: But they don't have a presentation. If they had a presentation I would grade the presentation. Exactly what did you do and I would ask questions, and ok they did the prototype, what else did you come up with, the best possible solution those kinds of things.

Interviewer: We might not be able to do every step [of the EDP] with these, but maybe you could say if the prototype was worth ten points what makes it a 10. This is number one... how would you assess this one [student project]?

Frieda: He did pretty good. In terms of looking at things we went over and the things he said about how he wanted it to work and it actually worked the way he wanted it to work. It looks like he has a good understanding of gears.

Interviewer: Why do you say that?

Frieda: Because you can see he used gears and on the inside and his was also a touch sensor... he knew if you touched it, it would go ... I think it kept going forward unless you touched it. It looks like he has a good understanding of a lot of things in terms of the sensors, gears, speed from looking at the tires and the gears. I probably would give this probably a 90... I think he did pretty good.

Frieda is quickly able to see how her strategies for assessing students' engineering project work related to how she assesses activities employing the scientific method. She suggests assigning categories in a rubric to each of the steps of the EDP (the eight steps of the Massachusetts Curriculum Frameworks EDP in this case). Considering that the unit focused on developing students' abilities to engage in the EDP to create a physical solution to a specific problem or need, this appears to be a worthwhile and appropriate strategy for assessment. However, when asked to apply this rubric to one of her student's projects, Frieda was quite vague in identifying what the student did and did not do well. She stated that, "he did pretty good," because "it actually worked the way he wanted to work." When asked to explicate the student's "good understanding of gears," she stated, "you can see he used gears" and it had a touch sensor that "kept it going forward unless you touched it." For Frieda the presence of these features demonstrated the student's understanding of sensors, gears, and speed justifying a score of 90 (out of 100). She does not explicitly connect any of this "good" work back to the steps of the EDP. Her original justification for assessing the eight steps of the EDP was "if they did every step, then probably everything would be sufficient and it wouldn't be falling apart and [they would know] exactly what their creation was." However, her application of the rubric primarily focuses on whether or not the creation worked the way the student wanted it to and not on how the student engaged in the steps of the EDP. This is not surprising as it can be quite difficult to accurately assess engagement in a multi-step process for a classroom full of students each designing and creating unique prototypes.

The claim made in this paper is that assessing engineering-based STEM curricula is extremely challenging and teachers will need extensive professional development in this area. To support this claim, we will present the results from a study of six middle school teachers as they embarked on teaching a 15-hour engineering design curriculum following a one-week (40 hour) professional development workshop. The goal of the study was to understand the various types of teacher knowledge the teachers used and developed over the course of implementing and engineering design curriculum. The data presented in this paper comes from one-on-one interviews (each approximately 20 minutes in length) with the teachers where they were asked to talk about designing a rubric for their students' final engineering projects.

Background

Introducing engineering design based activities into K-12 classrooms is often an exciting endeavor for both students and teachers. Routinely, these sorts of classroom activities lead to lively participation from students and the production of rich artifacts seemingly teeming with the application of deep STEM concepts, practices, and processes. However, the excitement associated with these activities does not always translate to accurate measurements of what students are or are not learning. Engineering design-based activities are relatively new in K-12 education and the assessments teachers are familiar with from their science or mathematics teaching are not so great at assessing the complexities introduced with prototype solutions to open-ended design scenarios.

Within the research community, the need for better assessment tools and methods has been well-established [1], and even argued as "our essential new priority" by scholars like Songer and Ruiz-Primo [2]. To date many researchers have focused on test development as a priority without emphasizing the critical role of teachers and their classroom assessment practices. There are in fact very few research studies that examine the relationship between teachers' assessment practices and student learning or evaluate teacher pedagogical content knowledge from the perspective of assessment.

However, assessment tools are only useful if they are implemented properly. In formal educational settings, a recent report from the National Council of Teacher Quality found that only 3% of teacher preparation programs provide adequate instruction on the use of assessment [3]. The challenge for engineering is two-fold: negative attitudes about assessment amongst teachers and complexity in identifying key knowledge and skills student learn through engineering.

In 2010 and 2012 INSPIRE, Institute for P-12 Engineering Research and Learning, sponsored the 1st and 2nd P-12 Engineering and Design Education Research Summits. At both, assessment was overwhelmingly cited as an occurring need identified by Kluin, Purzer & Cardella [4] and noted by Sneider, one of the "grand challenges of engineering education" [5].

One of the main barriers to assessing engineering in the K-12 is the need to understand engineering at this level. Engineering is often categorized by its defining characteristics. Moore et al. [6] have defined engineering through twelve key indicators of quality K-12 engineering. Together these indicators provide a framework for characteristics of engineering that could be assessed. In the following sections, we will highlight some of the background literature relevant to the indicators that presented themselves in this study: (1) Engineering Design, (2) Engineering Thinking (with an emphasis on Creativity), (3) Engineering Tools, Techniques, and Processes, and (4) Teamwork.

Engineering Design

Engineering design is at the heart of engineering practice. It involves iterations on the steps: define the problem, research the background knowledge on the problem, plan a solution, implement the plan, test the implementation, and evaluate the outcome [6]. Engineering design has been shown to have benefits to K-12 students in terms of gains in STEM content knowledge and process skills [7-13]. The EDP is highly iterative and provides pathways to multiple solutions. It also provides meaningful contexts to learning [7, 13, 14] and stimulates systems thinking, modeling, and analysis [15]. Research has shown that using a design context to teach science and mathematics can help students develop cognitive models of how systems work, communication skills, and the ability to synthesize ideas [9].

Creativity through Engineering Thinking

Engineering in the K-12 setting provides opportunity for students to use informed judgment to make decisions when solving problems [6]. Critical thinking skills can be improved by engaging students in hands-on engineering and design activities intended to foster knowledge, skills development, and problem solving [1]. Engineering activities foster the development of independent, reflective, and metacognitive thinking in K-12 students [6]. In particular, engineering thinking involves creativity and innovation. Creativity involves fluency (producing a large number of ideas), flexibility (producing a variety of ideas that fit in different categories or an ability to see things from different perspectives), and novelty (producing ideas that are unique and original) [16, 17]. According to Shah and Vargas-Hernandez [18], "an engineering design must not only be novel (unusual, unexpected) but it must also satisfy some intended function(s) to desired specifications (have desired utility)" (p. 111).

Engineering Tools, Techniques, and Processes

The need for technological literacy is growing due to the increase in the prevalence of technological tools. The work of engineers involves the use of a variety of tools, techniques, and processes, as well as the development of technological tools that help solve problems. Students participating in engineering design activities at the K-12 level should become familiar and proficient with the relevant technologies [6]. This should focus on improving students' understanding of the technological world. The understanding of the central role of materials and their properties is an essential feature of engineering solutions [11]; therefore, students should learn to notice and reflect on the structure, function, and behavior of a process, a device, or a natural phenomena [7]

Teamwork

Teamwork is central to the work of engineers, as the development of most solutions requires multiple people with diverse expertise, perspectives, and skillsets. Engineers collaborate with professionals across disciplines gathering multiple perspectives to garner the most effective design solutions [19]. Promoting engineering habits of mind, which includes collaboration [6], has been proposed as one of the three principles to guide engineering education design and delivery in the K-12 setting. K-12 students should be working in teams during engineering activities to foster the development of teamwork skills [6, 20]. Furthermore, teamwork in the form of cooperative learning has proven to be an effective pedagogy for enhanced learning for students in K-12 education [21-24]

Study Design

The study presented in this paper investigated six middle school teachers as they embarked on teaching an approximately 15-hour engineering design curriculum following a one-week professional development workshop. The goal of the study was to understand the various types of teacher knowledge the teachers used and developed over the course of implementing and engineering design curriculum [author citation]. The data presented comes from one-on-one interviews (each approximately 20 minutes in length) with the teachers where they were asked to talk about designing a rubric for their students' final projects. They were then asked to apply this rubric to a few sample projects from their class. Details regarding the teachers' implementations of the curriculum can be found in other publications by the first author [Author citations].

The Teachers

The six teachers who participated in the study all taught in the Boston Public Schools in urban schools with high populations of underrepresented minority populations. The teachers all participated in a weeklong professional development workshop where they learned how to teach an engineering-design based unit using the LEGO MINDSTORMS robotics toolset. Table 1 below provides details regarding teaching experience, grades taught, subjects taught, and educational preparation for each teacher.

Teacher	Years experience	Grade(s) teaching	Subject(s)	Bachelor's degree	Master's Degree
Frieda	0 (in 1st year)	7, 8	Science	Biology	Teaching
Monica	3	6	Mathematics	Finance	None
Scott	3	7	Mathematics & Science	Humanities	Teaching mathematics*
Victor	5	5	General	Business	Teaching
Sonya	16	K-5	Computers	Anthropology	Teaching computers
Maria	17	5	General	Mathematics & physics	Bilingual education

Table 1: Teacher teaching and education profiles.

*Note: Scott was currently enrolled in a Master's in Teaching Mathematics graduate program.

Discussion of Results

The following results are broken into two sections. The first set of results in this section show the categories the teachers noted as things they would look to assess in a rubric they would use for their students' final projects. The second section takes a closer look at the teachers' detailed explanations of how they would apply these impromptu rubrics to a few of their students' final projects.

Each teacher was asked to think of the categories they might use for a rubric to assess their students' engineering projects. Table 1 presents the categories each teacher stated they might use.

Table 2: Teachers' rubric category choices

	Rubric Categories						
Teacher	**Creativity & Originality**	**EDP steps**	**Technical aspects***	**Solution Quality**	**Teamwork**	**Organization**	**Other**
Frieda	☑	☑ (test & evaluate)	☑				☑ Purpose/ need
Monica	☑		☑ programming/ effort	☑ appearance durability			
Maria			☑ mastering skills and concepts		☑	☑	
Scott		☑					
Victor	☑		☑ proficiency	Structural integrity			☑ redesign Overall design
Sonya	☑	☑ design	☑ programming	☑ technical difficulty ☑durabilit y	☑		

The table illustrates that a number of categories were common across multiple teachers. For example, creativity and originality (similar concepts) were common for 4 of the 6 teachers. Other categories represented by two or more teachers included: EDP steps, design or overall design; technical knowledge/proficiency; durability; and teamwork. Considering the elements reviewed in the prior Background section of the paper, the teachers are identifying relevant knowledge, skills, and abilities for engineering. The following sections expound each of these categories.

Creativity or Originality

Creativity or originality was the most common criterion for success noted by the teachers. Creativity has become a buzzword among engineering and STEM education reform as educators attempt to teach students to engage in critical thinking skills leading to innovative, unique solutions or ideas. However, it is a seemingly elusive construct to define, let alone measure. Without a systematic, pre-determined method for measuring creativity, a teacher is most likely to base such a measure on their "gut" reaction to how creative something is. Generally, they measure against things they have already seen or among the solutions in the class. Needless to say it is a very subjective criterion to assess. Monica states this criterion as the most important in her assessment, but struggles to provide a clear explanation as to what exactly makes up an original solution:

> Monica: One of the first things that I think is important is **originality**. I prefer when they have an original idea. If they have an idea that is already invented and they want to improve upon it that is fine, but I prefer that they have an original idea. It means they have put some thought behind it.

Monica gave the clearest picture of what she mean by originality, while the other teacher primarily looked for, "was it creative?" as stated by Sonya.

The teachers' application of the creativity criterion to their students' projects did not give much more insight into how they were assessing it. Frieda made comments such as, "it looks to be creative," and assigned 10/10 points to a group because, "that was pretty creative." Likewise, Monica stated, "with originality I would give this one a 4/4… it's very original," and just 3/4 for another stating, "they wanted to do a walking stick at first and I wanted something a little more original so I would give them … and I'm a little easy… probably a 3 on this." Sonya gave slightly more insight with her comments relating creativity to her ideals and elegance, "I thought it was extremely creative, I liked the idea," and, "it was a very creative idea. It was very elegant."

Design, EDP Steps

Four of the six teachers also identified the overall design or how the team completed the steps of the EDP as an important criterion to measure. Both Frieda and Scott stated using the steps of the EDP to assess how successful the students were in completing their projects. Frieda suggested, "if they did every step then probably everything would be sufficient and it [the final prototype] wouldn't be falling apart and [the students would know] exactly what their creation is." She later hinted toward successful designs as relating to a specific purpose or need as she critiqued one design, "I don't think he definitely knew who he was targeting it for, and I don't think he thought about all the different aspects—which people could use [it], or how it could be used—it was pretty narrow." She was hopeful that the EDP if applied in a systematic, careful manner that the students' projects would demonstrate success by purposefully addressing a specific need for target group of users and did not fall apart. However, when she attempted to apply the EDP steps as a rubric, she quickly realized she did not have adequate information to evaluate each step of the EDP leading her to reconsider other criteria for the rubric.

Similarly, Scott thought the rubric should assess the students' application of the EDP, which he stated as a primary learning objective of the curriculum. He referred to the project worksheets the students completed as they designed, built, and tested their creations as a primary source for understanding how well his students knew and applied the various steps of the EDP. He then provided a clearly detailed explanation of how he would refer to the sheet and ask the students questions to gather data for such an assessment.

> Scott: That's why I would probably rely a lot on the sheet because the sheet would tell me if they really did brainstorm, if they really did research. I could ask them why did you choose this and if no thought had gone into it they would probably say I don't know, but if a lot of thought had gone into it on that particular step and even if they hadn't filled out the sheet you could ask them what were some of their other choices, which would go back to the other step.
>
> Interviewer: It seems like these first three steps are reliant on asking students questions and seeing the sheet they may have filled out... if we talked about the solution itself the prototype.
>
> Scott: So then you would ask ok so why did you choose that solution see if the reasons reflect they had some choices and if the choices were based on certain things. And it would be great if they mentioned things like things we had talked about like cost/benefit or those types of things. And then when they test it... how did you test the solution? What were you looking for? Those kinds of things... what went wrong? You could just go through each step and ask questions like that, and if they did put a lot of thought into it they would have answers to those questions.
>
> Interviewer: So a lot of the assessment is coming from knowing what the students have done, asking them questions about it, their thought process behind it...
>
> Scott: For me just using the EDP as a guide to go through and ask questions about it.

Scott has articulated a very thoughtful approach to assessing students' engineering design work focused on asking students to explain and justify their approach to addressing the need at hand. Given the time and direction to develop and then implement such an assessment strategy may indeed hit upon the sorts of individual and team learning and development gains we want to see teachers assessing.

Durability

Monica described durability as, "they've put some effort into making it durable so it doesn't break, doesn't fall apart… what we're trying to teach them is to make something that is usable." Victor expressed he would ask, "how are you structurally?" referencing two designs wondering if the motor was sufficiently supported from below for one and whether the arms in front of the vehicle were "sturdy enough."

> *Team 1*
> Interviewer: How about structural integrity?
> Victor: The whole vehicle stayed together except that front part, and that was too bad. Probably 4 [out of 6].
> *Team 2*
> Interviewer: Structural integrity on this one?
> Victor: Probably a 3 because that piece kept breaking off like you wouldn't believe. It just ... I think in the first one (Team 1) they attached it to the chassis of the and then attached it to the top of the car, where this one (Team 2) was just haphazard (attached only at the top).

Monica's and Victor's focus on the durability of their students' designs allude to a desire that students learn to troubleshoot problems and through adequate iteration as they redesign are able to rectify such issues. However, they are not able to articulate this clearly and focus primarily a surface feature of the design.

Technical proficiency

Assessing the technical details of the final projects was an after thought for some of the teachers requiring the interviewer to restate the teachers' references to gears or how well it worked to something more technical in nature. As one may have been able to infer the developing theme, the teachers' again struggled to provide specifics on how and what kind of technical knowledge their students applied to their designs.

> Sonya: Ok. This one I think it was definitely technically ... giving him an A. I thought it was extremely creative, I liked the idea, I thought it was technically difficult... very challenging.
>
> Interviewer: What made it difficult, technically?
>
> Sonya: The mechanism of how the arms... and that it was going to climb stairs... and he originally kept saying that he wanted to have hydraulics. I loved his original inspiration for it and he had to redesign and he was one of those that kept going through the redesign phase and he had some setbacks and ... he's a slacker kid that really stepped up.

Sonya recognizes something that makes the creation technically advanced (namely, the mechanism that helps it climb stairs), but maybe not quite able to identify what exactly makes the configuration technically difficult. This may be due to her own lack of engineering or technology knowledge in this case. Maria comments on her students' technical know-how:

> Maria: Technical knowledge it was ok because they were both working very hard. One day Student A was absent and Student B was doing. I don't know for some reason he destroyed the whole thing and the next day Student A came back and rebuilt the whole thing. I saw that both of them are very strong at using their hands to put together. Technical I can say is like an intermediate going to advanced.
>
> Interviewer: Part of that you can see the gears here (references picture of project)... what would you say about how they arranged the gears here?
>
> Maria: The gears... well they had a lot of trouble to do the gears. They found out it was a very slow car, but I say maybe you can change the wheels and that may help you. Still I think they could be intermediate for knowledge and putting together the gears.

Again the description of how or why the team rated as an intermediate or advanced for their technical know-how is vague. Maria mentions, "they had a lot of trouble to do the gears," but were able to put them together. Putting gears into a LEGO creation does not necessarily predicate knowledge of how they work or why they are used.

Teamwork

Working in teams is common among classroom engineering design activities as it imitates practice and allows teachers to accommodate the entire class with fewer materials for these resource-intensive activities. Similar to the criteria already discussed, teamwork is also difficult to systematically measure in the given classroom context. Maria and Sonya both acknowledged they would look for how well the students worked as a pair or team. When asked about the main learning objectives for the unit, Maria shared that while, “it’s not part of the curriculum, but [I was] trying to make them understand that they have to work in groups because my students have a problem with that.” Sonya described it as, “was one person dominant or were they collaborative?”

Maria details her assessment of one team’s teamwork as:

> Maria: Student A ended up doing the whole thing because Student B was just sitting around doing nothing. But he was very good at testing the thing. To create the whole thing it was student A. So for teamwork [I would rate them] beginners.

She rated another team more highly stating, “They are very good at teamwork. They were very nice to each other, very respectful of each other, helping each other. They could be [rated as] intermediate or advanced.” While Sonya’s assessment of teamwork was as follows for two teams:

> *Team 1*
> Sonya: And teamwork I would say it was a B (on a A-F scale). He did a little more, but they were both engaged in it.
> *Team 2*
> Sonya: We’ll give a D for teamwork. She did nothing.

Both Maria and Sonya have identified working in teams as important to what their students were doing. They commented on their general impressions on how the students interacted within their teams; however, they do not provide many details as to what teamwork skills the students learned or developed. They assess teamwork based on individual effort, which is certainly a component of good teamwork, but their observations do not fully capture how the team negotiated the task at hand and implemented teamwork skills.

Conclusion

Doing engineering involves processes that are new to many teachers. Part of the difficulty is the complexities introduced related to diverse outcomes that can be examined such as (1) the quality of processes students used to arrive a solution; (2) collaboration and social interactions that not only support individual learning but also timely completion of a project; (3) the quality of a solution from a technical perspective; and (4) the quality of a solution from a creative perspective. Teachers attempted to measure these outcomes. However, their attempts were often ambiguous. In addition, assessment of technical skills was at the product and team level. There were few attempts to assess student learning at the individual level.

According to a recent NRC [25], tasks designed to assess NGSS performance expectations should have the following characteristics:

- Tasks should have multiple component related to scientific and engineering practices and disciplinary ideas and crosscutting concepts (Note: some evidence that teachers are concerned about different aspects of learning)
- Reflect progressive learning (Note: One teacher appears to talk about progressive improvement of a student)
- A system for evaluating a range of student products that provide specific information useful for formative purposes (Note: some awareness for need for diverse data and rubrics)

In agreement with the NRC, we conclude that teacher professional development specific to assessment is crucial and should be thoughtfully integrated with the any training specific to the development and delivery of engineering design curricula.

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