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Engineering Education in the Middle School: Exploring Foundational Structures

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BACKGROUND

The recently released *Mathematics, Engineering & Science in the National Interest* report (May, 2012) highlights the universal perspective that an education in these disciplines is essential to a nation's future prosperity. Although studies in STEM (Science, Technology, Engineering, Mathematics) are being implemented across many schools, progress to date has been slow especially with respect to incorporating engineering experiences in the middle and primary grades. Our concerns for the limited attention given to engineering in STEM and the low uptake of university engineering courses in universities, prompted us to conduct a longitudinal project on engineering education across grade levels 7-9.

PURPOSE

The overall purpose of the engineering activity addressed here (*Investigating Foundational Structures*) was to engage school students in devising, testing, and evaluating a real-world engineering problem demonstrating the link to mathematical principles and science inquiry. Addressed are 8th grade students' responses to this activity, in which they experimented with ratios of supplied materials in constructing a sturdy, model pylon to support a wind turbine. Questions addressed include how students perceived the goal, how they changed the control ratios in creating their experimental mixture, their understandings of the foundational materials, and their perceptions of the limitations of their constructions and ways in which they would make improvements.

DESIGN/METHOD

A design-based research approach, specifically, a design experiment, involving the learning of students, teachers, and researchers was adopted (Kelly, Lesh, & Baek, 2008). Data collection included student artefacts and video/audiotaping of group work and classroom discussions. Data analyses involved ethnomethodological interpretative practices, with data progressively reviewed, transcribed, coded, and examined for patterns and trends in the students' developments using constant comparative strategies (Creswell, 2012).

RESULTS

Students' perceptions of the goal of the activity suggested that, while they recognised the importance of carefully considering the material ratios and the need to build a pylon of maximum strength to withstand various forces, there was nevertheless a focus solely on the object of construction. Students' decisions on how to apportion the respective materials revealed varying understandings of their properties and roles, with some important features of the materials being overshadowed by their perceived disadvantages.

CONCLUSIONS

Engineering activities can enrich existing school curricula, with the development of foundational understandings and design processes that can be applied to solving problems across domains. Facilitating STEM activities in schools is a step towards opening up their prospects for possible career choices, such as engineering. More research is needed to understand how school students engage with STEM education so that we might improve processes to capitalise on high-level learning opportunities in these fields.

KEYWORDS
Engineering education; middle school; mathematics/science curriculum

Background

Concerns regarding the severe skills shortage in engineering have been repeatedly expressed in recent years. The March 2010 media release of the Australian National Engineering Taskforce survey of nearly 2400 engineers revealed the “gaps in engineering skills and capacity at workplaces across Australia,” highlighting “the potentially catastrophic impacts of Australia’s engineering skills crisis.” More recently, the *Mathematics, Engineering & Science in the National Interest* report (May, 2012) pointed out the universal perspective that an education in these disciplines is essential to a nation’s future prosperity and that action needs to be taken to improve the current situation.

The Australian Government (DEEWR, 2010) has been calling for such action along with the Australian Business Council, which has argued that “too many young Australians are being left behind by our school education system,” beginning with early learning in mathematics and science (www.bca.com.au). The Council has further maintained that many aspects of our school system “have not changed since the 1960s” (26 August, 2007; http://www.bca.com.au).

A strong focus on the need to reconceptualise education systems to meet the demands of the 21st century is evident across many nations. For example, the National Research Council (USA, 2009) stressed that a “new, educated workforce, one that is more open, collaborative, and cross-disciplinary” (p. 19) is needed. Indeed, Katehi, Pearson, and Feder (2009) emphasised that the new challenges posed by the increasing complexity, competition, interconnectivity, and technological dependence in our world today “cannot be met by continuing education as usual” (p. 49). In particular, the STEM area (Science, Technology, Engineering, Mathematics) in schools requires greater acknowledgement and focus to meet the needs of the 21st century (Bullen & Haeusler, 2010; English, Hudson, & Dawes, 2011).

Engineering education in schools is an emerging and promising approach to preparing young scholars for the world of tomorrow. Unfortunately, the engineering component of STEM has received almost no attention in schools, especially in the middle and primary school years (Bullen & Haeusler, 2010). As the National Academy of Sciences (2009) stressed, it takes years or decades to build the capabilities societies need: “You need to generate the scientists and engineers, starting in elementary school and middle school” (p. 9).

In addition to increasing students’ awareness of and interest in the field, engineering education can make a rich contribution to the new Australian National Curriculum (ACARA, 2011) across mathematics, science, English, and technology. More specifically, engineering education can enhance students’ learning with its focus on design processes, problem solving, reasoning, creative and flexible thinking, and dealing with mathematical and scientific situations within their personal and subsequent work lives (e.g., Borgford, Deibel, & Atman, 2010; Katehi et al., 2009).

Our concerns for the limited attention given to engineering in STEM studies and the low uptake of engineering courses in universities (e.g., Engineers Australia, 2012; Kaspura, 2011), fuelled by school students’ limited interest in and appreciation of mathematics and science in engineering feats, prompted us to conduct a longitudinal project on engineering education across grade levels 7-9 (funded by an Australian Research Council Linkage Grant [LP0989152]). This paper reports on one component of the project, namely, grade 8 students’ responses to an activity implemented during the project’s second year, that of *Investigating Foundational Structures*.

Purpose

The overall purpose of the engineering activity was to engage school students in devising, testing, and evaluating a real-world engineering activity demonstrating the link to mathematical principles and science inquiry. As indicated in the methodology section, the Investigating Foundational Structures activity required students to experiment with ratios of supplied materials in constructing a sturdy, model pylon to support a wind turbine.

Of interest in the students' responses to the activity were the following:

1. How did the students perceive the goal of the activity?
2. How did the students change the ratios of the control mixture in creating their experimental mixture?
3. What understandings of the foundational materials did the students display in constructing their pylons?
4. What were the students' perceptions of the limitations of their constructions and ways in which they would make improvements?

Methodology

Participants

During the second year of the project, four eighth-grade classes completed the Investigating Foundational Structures activity. The classes, who had participated in the first year, were drawn from three private schools, namely, an all-female school, an all-male school, and a co-educational school. Classes completing the present activity included one from each of the same sex schools and two from the co-educational school.

Design

The project involved design-based research, specifically, a design experiment, involving the learning of students, teachers, and researchers (Kelly, Lesh, & Baek, 2008). Comparative case studies (six focus groups) were also included (Yin, 2003). In collaboration with the teachers across the three years, we designed and implemented engineering activities addressing a range of fields. Teacher involvement in the development, implementation, and assessment of the activities was a critical factor; hence, the conduct of regular teacher meetings was essential.

Data collection included student artefacts (student work books and photos of their products) and videotaping and audiotaping of the work of all focus groups and whole-class discussions; all taping was transcribed. Data analysis involved ethnomethodological interpretative practices (Erickson, 1998), with data progressively reviewed, transcribed, coded, and examined for patterns and trends in the students' developments using constant comparative strategies (Creswell, 2012). Given this ethnomethodological approach, the analysis was primarily of a qualitative, rather than quantitative, nature. With the small sample sizes, our quantitative analysis was limited to response frequencies, which we considered added support to our qualitative findings.

The analysis for the activity reported here was based on all the transcribed data from the six focus groups (two in each school) and the booklet responses from 16 groups (including the focus groups) across the four classes. Anecdotal comments supporting the findings were drawn from both the transcribed data and the students' written responses in their booklets. The calculation of frequency responses was drawn from the booklets. As indicated in the procedures section, the students responded to five booklet questions in evaluating their structural design, understanding of material combinations, and reflection around the construction process.

Procedures

The Investigating Foundational Structures activity engaged students in elementary chemical and civil engineering understandings and was implemented over four, 40-minute sessions. As an introduction to the engineering education activity, students were provided with visual stimuli on foundational structures and asked preliminary questions such as: "What might happen if you built the foundation of a bridge or structure on a sand dune? What about the Pyramids in Egypt? And what do you know about the Tower of Pisa in Italy?" A short, hands-on activity (Jenga: http://en.wikipedia.org/wiki/Jenga) introduced concepts around foundational structures followed by discussing materials that comprise foundational structures (e.g., concrete as a mixture of: cement, fine aggregate [sand], course aggregate such as gravel or crushed stone, and water). As the upcoming hands-on engineering activity would involve making and testing pylons, another real-world example was discussed with the students, that is, the use of pylons for wind turbines (see http://www.waubrawindfarm.com.au/Civilconstructionworks.htm). Students listed materials used to make the pylon of a wind turbine then investigated sample materials (crushed rock, sand, plaster of Paris – as a cement substitute) and used a graphic organiser to draw, define and describe the sample materials (e.g., size, colour, and shape of each material). After investigating each material, they were provided with further information about each (e.g., http://science.howstuffworks.com/dictionary/petrology-terms/sand-info.htm & www.learner.org/interactives/rockcycle/types.html). Students were given the task of making a wind turbine pylon using the sample materials, then wrote a hypothesis about the sturdiness of the combination of materials selected to make the pylon.

In constructing the model pylon, students calculated the volume of the cylinder and decided on the ratio and volume (cm^3) of materials to be used. They placed the materials inside small cylinders (PVC pipe approx. 20mm diameter and 100mm long) and these were allowed to dry, set, and cure to replicate engineering practice before the next engineering education lesson. Ratios and volumes of each material were recorded in a table and were to be evaluated according to the control mixture ratio, which was 3 parts crushed rock: 2 parts sand: 1 Plaster of Paris: 1 water. After predicting the mass that would weaken the experimental structure, students tested their two pylons (control and experiment) by using incremental masses (100g, 500g, 1kg, and 2kg) placed on top of the pylons while observing and recording cracks, signals of stress, performance, sturdiness, and suitability of each pylon. Students were asked to evaluate their foundational structure activity through a series of five questions: (1) Describe the intended purpose of your construction. (2) What did the results tell you when you tested your construction? (3) What were the limitations of your pylon? (4) Compare the performance of your pylon with the control/other mixtures in the classroom, and (5) How could you improve your design to make your pylon stronger?

Results

Perceptions of the goal

On completion of the activity, students' responses to the first question varied considerably (*n*=55 responses across all classes, excluding duplicate and nil responses). Responses ranged from reference only to the object of construction through to a focus on the proportions of materials that would make the strongest pylon, one that would withstand particular pressures or forces. The most basic response was prevalent in the all-male school classroom, with 42% of responses (*n*=26 responses, excluding duplicates) referring only to building a pylon (e.g., "To make a small pylon for a wind turbine"). Teacher factors in introducing the activity in this all-male classroom cannot be discounted here, although 31% of their responses did acknowledge the goal as building a pylon that would "hold the most weight" and 15% focused on the materials and their ratios in producing the strongest pylon.

A focus on the goal as determining the most effective combination of materials to construct the strongest pylon was most evident in the co-educational school classes (*n*=22 responses, excluding nil response), with 32% referring to material combinations. Consideration of the goal as only withstanding the most weight was given by 36% of the responses in these co-educational classes and by four students in the all-female school (*n*=7 responses, excluding nil response). Across all classes in the three schools, there were only three references to the goal of withstanding specific forces such as wind, precipitation, and gravity, two of these being in the all-female class.

Changing the control mixture ratios

In preparing the activity, we purposely did not make the ratios of the materials for the control mixture "ideal"; rather, we incorporated a greater proportion of crushed rock. Not surprisingly, this resulted in substantial debate over the ratio of crushed rock to the other materials in the students' construction of their experimental pylon. For example, students debated whether there should be more or less crushed rock than sand and how the amount of water might affect the resultant mixture:

Jane: So do we still think there should be the most rock or...?

Lesley: Is there any way we can do half a part of water?

Jane: I don't think that's a good idea.

Mary: But we shouldn't do more water...

Lesley: So the more sand we put in, we don't need any more water.

Mary: What would happen, just a sec, what would happen if you put less crushed rock and less and less water?

The retention of the same proportion of Plaster of Paris (one part) added to the debate, as indicated next. In deciding on the ratios of materials for their experimental pylon, the students were especially concerned with the ratios of crushed rock to sand, with water of less concern, albeit recognising its importance in forming their mixtures. Of the 16 groups across the three schools, 15 reduced or removed the control proportion of crushed rock (ranging from 0 to 2.5 parts), with one group maintaining the control proportion. As discussed next, there was considerable debate over the ratio of sand to the other materials, with five groups retaining the control proportion while eight groups increased it (7 groups chose 3 parts, 1 group chose 4 parts); three groups reduced the sand proportion to 1 part. In considering how much water to include in their mixtures, nine groups retained the control proportion (although one of these groups decided to try 0.75 and included this in their table). Four groups reduced the water content, deciding on 0.5, while three groups increased the proportion to either 2 or 1.5 parts water.

Understandings of the foundational materials in pylon construction

From the analyses of the six focus groups' transcripts in constructing their pylons and the responses of all 16 classroom groups to question 2 (what the results informed the students on testing their pylons), there emerged a number of different, often contrasting, understandings of how the materials contributed to constructing a strong pylon. While all but one group reduced the proportion of control crushed rock, how to do so in combination with the remaining materials was problematic for the students. Considerable debate was held on the benefits and limitations of crushed rock and how these might be addressed in selecting proportions of the remaining materials. Students expressed concerns that too much crushed rock would cause air bubbles and rough surfaces, and that more Plaster of Paris would be needed to compensate for this. Across all responses of the 16 groups (*n*= 56 responses in total, with some responses commenting on more than one factor), 23% of the comments referred to the need for either less crushed rock and/or more plaster. Comments here included:

- The more plaster makes it stronger and less rocks makes it weaker as it creates more gaps.
- Our results told us that the concrete was much stronger when there was (sic) less crushed rocks. This possibly might have been stronger because there was more room for the Plaster of Paris.

The above comments are interesting in that they demonstrate that the students' understanding is partially correct. While the students appeared to understand the need for a balance of the different size ranges (gravel, sand, and fine plaster) to combine effectively to form fewer air voids, their assumption that more plaster would make the structure stronger indicates the need for further understanding.

The ratio of sand to the remaining materials received mixed responses. While the students could not change the one part plaster (although one group did so) and saw this as a limitation, they were divided on whether their chosen proportion of sand would strengthen or weaken their structures. Of the 16 groups, two chose fewer parts of sand than crushed rock, while five chose equal parts of both, and seven, more sand than crushed rock. Sand was frequently viewed as strengthening the structure, along with plaster and an appropriate amount of water. Initial discussions on determining their experimental mixture of the two focus groups in the all-female school illustrate some of the debates that took place:

Focus group 1

Tey: Well, I don't think you should use much sand cause it would blow away and...

Elly: Sand separates and moves easy cause it's a looser substance...

Tey: But then you don't want too many rocks cause then they would fall apart.

Neah: Need more water.

Elly: Yeah, I reckon a little bit less sand but a bit more water it would be fine if we left crushed rock the same.

Focus group 2

Kathy: So you want to keep our ratio like that (1:2:1:1)?

Suzie: No, I think we should change it to 7 (parts)...

Kathy: So long as our sand beats our crushed rock.

Penny: Should we change the sand to 3 (parts)?

Kathy: Um, think about it, sounds like a good idea, doesn't it?

Perceptions of limitations and improvements needed

In response to question 3, students mainly identified material and structural limitations in reflecting on their pylon creations. Across all responses of the 16 groups (n= 57 responses in total, with some responses commenting on more than one factor), 42% of comments made mention of material limitations: these pertained to the proportions students used, the features of the materials provided, and the limited amounts that could be used. Student comments here included, "The limitations were the materials used, the size (thickness) of the pylon, the size of the weights"; "There wasn't enough plaster that could be used which affected the strength"; "You could only have one Plaster of Paris and a limitation of a max of three of each other part"; and "We had to use Plaster of Paris instead of cement and we had a set amount of that, that we could use". It is worth commenting here that the retention of the one part plaster was to allow direct comparison between designs, and that the use of plaster instead of cement was for safety reasons.

Further, a few students recommended adding or changing materials such as including steel reinforcement and using cement instead of plaster. One student explained to his class, "You need a metal base that actually goes into the ground so it can actually stand up properly even though there is wind coming so there could be a hurricane coming in, who knows, um so then it doesn't topple over". This student is demonstrating a higher level of understanding in that he is considering a systems approach to solving the problem rather than focusing on the individual task.

Concerns expressed over structural limitations were incorporated in 35% of the responses and included references to the base not being flat, the tilt of the pylon, the need for more compactness, and better weight distribution. Indicating an awareness of the limits of small-scale experiments, students' responses here included, "The limit of our pylon was actually the bottom of the foundation (the bottom wasn't flat);" "The ability for our pylon not being able to be balanced properly and not to break;" and "It wasn't strong so it couldn't hold a very large weight. It wasn't compacted well so it just crumbled".

The remaining limitations expressed by the students included poor handling of the materials (e.g., "a lot of mixture was spilt over the cardboard", insufficient time to construct a sturdy pylon, and "intelligence" with respect to knowledge of the materials (e.g., "background knowledge of cement/concrete"). The need for more time to research and test their pylon was mentioned in a reflective class discussion in the all-female classroom: "We had less time and you know less time to research what could happen, what could go wrong; plus you don't know exactly where you would have to build anything on".

In identifying ways in which they would improve the design of their pylon to make it stronger, 55% of all the comments (*n*=64 total responses, with some responses commenting on more than one factor) made reference to changing the ratios of the materials, with most indicating proportions of specific materials they would alter. With respect to changing the ratio of specific materials, students were more focused on adding more sand (13 such comments) and more plaster (14) than reducing the amount of rocks (9). Recommendations for altering the proportion of water were less common (10 such comments), with only two recommending increasing the proportion.

Discussion and Concluding Points

Prior to reflecting on the findings, it is worth noting some limitations of the activity and its implementation, and the resultant data collected. Although the students were actively engaged in building their pylons, they did express some frustration in the fixed amount of Plaster of Paris they were permitted to use. As indicated previously, this feature was included to allow for comparative testing, and in hindsight, could have been explained better in the activity. Nevertheless, removing this restriction might have provided greater insights into the students' understandings of how the foundational materials interact in producing a sturdy pylon.

The implementation of the activity was conducted according to the guidelines we created (with the teachers' input) but the data transcripts of whole class discussions indicated some variation here. For example, some teachers conducted a more in-depth discussion of the students' finished products than others, with greater consideration given to what the students learned and how they might extend the experiment to improve on their overall design.

With respect to data collection and analysis, students' responses to the booklet questions resulted in rich data, but at the same time, made analysis more complex when several factors were incorporated in the explanations given. There was also a limitation with respect to the small number of students in the all-female class, making class comparisons less robust than desired. This limitation could not be overcome due to the way in which the school had structured this particular class. Nevertheless, the triangulation provided by analysing the transcriptions of the focus group and whole-class discussions strengthened the overall validity of the findings.

Results from the analyses suggest a number of implications for implementing engineering education in school classrooms. First, students' perceptions of the goal of the activity suggested that while they recognised the importance of carefully considering the material ratios and the need to build a pylon of maximum strength to withstand various forces, there was nevertheless a sole focus on the object of construction. Increased attention to the goal of an engineering activity is needed in the planning of future learning experiences. This increased focus continues to be highlighted in calls for enhancing students' problem solving in mathematics and science, but approaches to doing so are mixed and in need of further research (e.g., English & Sriraman). Engineering-based problem solving, which includes a focus on design processes in addressing the problem goal, provides a strong avenue for developing the future-oriented problem-solving skills our students increasingly need (Borgford et al., 2010; Heywood, 2005; Reidsema, 2005).

Second, students' decisions on how to apportion the respective materials revealed varying understandings of their properties and roles. For example, while there was general recognition of some disadvantages of using too much crushed rock, there nevertheless appeared some limitations in the students' appreciation of the role of this material. Likewise, the use of sand in creating a strong foundation revealed mixed views on how it would interact with the other materials. Ideally, if time permitted, opportunities for further experimentation with these materials would have enriched students' learning, as indicated in one student's comment regarding the need for more time to research and test their pylon. Incorporating such opportunities within the implementation of classroom engineering activities is an important consideration in advancing students' understanding and appreciation of solving engineering problems. Furthermore, the interconnectivity between science concepts, mathematical measures, and engineering designs can become more apparent to students through problem-based experimentation in the secondary classroom.

Third, inviting students to reflect on the limitations of their constructions and the improvements they would make provide important opportunities for developing students' engineering design processes, as noted previously. Applying these processes to solving problems in their mathematics and science curricula, as well as in other domains, is another rich learning opportunity that engineering education offers to the middle and primary school years. Facilitating STEM activities in schools is a step towards opening up their prospects for possible career choices, such as engineering. More research is needed to understand how school students engage with STEM education so that we might improve processes to capitalise on high-level learning opportunities in these fields.

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