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STEM Integration in Sixth Grade: Desligning and Constructing Paper Bridges

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Abstract In this article, we report on sixth-grade students' responses to a set of problem activities that required the application of mathematics, science, and engineering knowledge in designing and constructing a paper bridge that could withstand an optimal load. Increasing students' application and awareness of their disciplinary learning and how they are applying this in an integrated STEM activity remains a challenge for educators. In addressing this issue, we included a focus on knowledge reflection and knowledge scaffolding through thought-provoking student workbooks. Among the findings are students' capabilities in planning, designing, reflecting, constructing, and redesigning. Students' planning indicated that they could justify their proposed bridge type/s, which often included a combination of types, by referring to their STEM understandings. At the same time, students remained cognizant of the problem boundaries. Students' design sketches indicated an awareness of the problem constraints, an understanding of basic engineering principles, and an application of mathematics and science knowledge. Students' reflections on their actions helped them to improve their bridge constructions. Suggestions are presented for knowledge scaffolding to facilitate the flexible and innovative application of STEM learning to new problem situations.

Keywords STEM integration · Mathematics, science, and engineering knowledge application · Engineering design · Bridge design/construction · Scaffolding, reflections

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Introduction

STEM integration has received substantial attention in recent years, with the notion of STEM itself and how its disciplines should be integrated open to debate. As Lawrenz, Gravemeijer, and Stephan (2017) noted in a recent special issue of this journal, there is general widespread support for STEM integration but more research is needed on how different forms and levels of integration can serve various instructional goals. In this article, we report on one approach to integrating primary school science, mathematics, and engineering, namely, through a set of problem activities in which engineering design served as the 'interdisciplinary glue' (Moore & Smith, 2014; Tank, Moore, Dorie, Gajdzik, Sanger, Rynearson & Mann, 2018). Although integrating science and engineering has received considerable attention (e.g. Capobianco, DeLisi & Radloff, 2017; Chen, Moore & Wang, 2014; Guzey, Ring-Whalen, Harwell & Peralta, 2017), further supported by the *Next Generation Science Standards* (NGSS, 2014), there appears less research on young students' disciplinary application when mathematics, science, and engineering are presented within the one problem activity.

Perspectives on STEM and Discipline Integration

Numerous interpretations of STEM education and integrating the STEM disciplines have appeared in the literature, with respect to the number of disciplines being addressed and the nature and extent of their integration (e.g. English, 2016; Honey, Pearson & Schweingruber, 2014; Moore & Smith, 2014; Moore, Stohlmann, Wang, Tank, Glancy & Roehrig, 2014b; Park et al., 2018). Ranging from a single discipline to multidisciplinary and transdisciplinary perspectives (Vasquez, Sneider & Comer, 2013), the notions of STEM and STEM integration remain vague and often contentious (Bybee, 2013). Two definitions are especially pertinent to the present study, highlighting the inclusion of engineering. Shaughnessy (2013) refers to STEM education as '… solving problems that draw on concepts and procedures from mathematics and science while incorporating the teamwork and design methodology of engineering and using appropriate technology' (p. 324). Importantly, a perspective on integrated STEM as enhancing, not adding to, an existing curriculum, and assisting students in understanding the interdependence among the disciplines is advocated by Bryan, Moore, Johnson, and Roehrig (2015). Highlighting intentionality and specificity in STEM integration, their definition refers to '… the teaching and learning of the content and practices of disciplinary knowledge which include science and/or mathematics through the integration of the practices of engineering and engineering design of relevant technologies' (p. 23).

A frequently cited difficulty with an integrated STEM activity is maintaining the integrity of the respective disciplines and ensuring students develop the required learning, especially when multiple content areas are addressed (English, 2016, 2017; Guzey et al., 2017; Honey et al., 2014; Shaughnessy, 2013). As Shaughnessy warned, programs can be referred to as 'STEM' but can be merely a STEM veneer, where approaches do not genuinely integrate the disciplines and hence learning in one area can override others. Furthermore, as with many problem-solving activities, students can simply work procedurally, often preoccupied with the task context, and lose sight of the disciplinary content (Reiser, 2004; Watkins, Spencer & Hammer, 2014). Likewise, as Guzey et al. (2017) argued, if integrated engineering-based projects do not reinforce students' application of science (or one or more of the other STEM disciplines), these projects can easily become 'arts and crafts projects'.

Several researchers have indicated that increasing students' awareness of their disciplinary learning and how they are applying this in an integrated STEM activity remains a challenge for educators (Bryan et al., 2015; Honey et al., 2014; Moore et al., 2014b; Nathan, Srisurichan, Walkington, Wolfgram, Williams & Alibali, 2013). Integrating STEM content per se does not guarantee that students will be aware of the contributions of the respective disciplines in problem solution (Moore et al., 2014b). Likewise, elementary teachers frequently lack the required pedagogical knowledge to effectively implement integrated STEM activities (Peterman, Daugherty, Custer & Ross, 2017). As a consequence of the foregoing concerns, it is not surprising that some STEM educators disagree with disciplinary integration. However, we argue that the disciplines do not stand alone in the real world and by adopting approaches to alleviate these concerns, integrating the STEM disciplines can lead to productive and rewarding learning.

Among such approaches is the use of quality instructional materials that highlight disciplinary connections and include adequate scaffolding across the curriculum (Peterman et al., 2017; Wendell & Lee, 2010). Students' reflections on their progress during a STEM problem activity, including how they are applying their learning and what they have learned during problem solution, have also been identified as a productive approach to addressing integration concerns (Capobianco et al., 2017; Wendell & Lee, 2010).

In this article, we report on sixth-grade students' responses to a set of problem activities that required the application of mathematics, science, and engineering knowledge in designing and constructing a paper bridge that could withstand an optimal load. Although bridge construction with a range of materials has been a popular classroom activity (e.g. Carroll, 1997; English, Hudson, & Dawes, 2012; Roth, 1995; teachers.egfi-k12.org/tag/bridge-design), a specific focus on younger students' application of multiple STEM disciplines supported by engineering design processes has received less attention in bridge activities. Indeed, it is only recently with the incorporation of engineering within the *Next Generation Science Standards* (NGSS, 2014) that there appears a formal, concerted emphasis on connecting science and engineering concepts and practices (Clough & Olson, 2016). As Clough and Olson emphasise, linking these disciplines has the potential to foster meaningful and robust learning of science concepts and also to establish a platform for new learning and applications. Their argument that particular science education goals have often been stressed at the expense of others indicates the need to focus more on the active and specific engagement of students in applying and recognising the contributions of the respective STEM disciplines, but not at the expense of important content knowledge.

To this end, our study incorporated detailed teacher notes indicating the STEM content and their connections, together with how the design processes supported learning. Structured workbooks incorporating questions that elicited both knowledge reflection and knowledge scaffolding were completed by the students as they worked the bridge activities. With respect to the students' bridge design and constructions, we address the following: (1) How did students apply their STEM knowledge (a) as evident in their preliminary planning and design sketch annotations, and (b) as they engaged in the processes of engineering design? and (2) What STEM knowledge was evident in students' documented reflections on their learning? Next, we elaborate on our framework of STEM integration by examining engineering design processes and how they can foster the development and application of disciplinary knowledge during problem solution. We consider the nature and role of these design processes in problem-solving and learning, together with knowledge reflection and scaffolding.

Engineering Design in STEM Integration

Design processes are at the core of engineering practice (Moore, Glancy, Tank, Kersten, Smith & Stohlmann, 2014a). In many nations, however, engineering and engineering design are not given the attention they warrant within STEM programs even though the discipline draws strongly on many areas of mathematics, science, and technology. Furthermore, designed-based STEM challenges are carefully structured so that both disciplinary knowledge and practices are utilised (Capobianco et al., 2017; Cunningham & Kelly, 2017; Wendell & Kolodner, 2014; Wendell & Lee, 2010). As such, engineering design-based challenges can facilitate STEM learning as students generate and implement solutions to a given problem, while at the same time come to appreciate what concepts they understand and do not understand (Capobianco et al., 2017).

There are several frameworks for describing engineering design (e.g. English, 2016; Lucas, Claxton & Hanson, 2014; Tank et al., 2018). As an iterative process, engineering design is frequently described as comprising a number of phases, including (a) problem scoping (understanding problem boundaries, identifying goal and problem constraints), (b) generating ideas and planning, (c) designing and constructing (sketching design, contemplating possible outcomes, transforming design into product), (d) testing and reflecting on outcomes (checking goal attainment and meeting of constraints), (e) redesigning and reconstructing (reflecting on first design, considering improvements, transforming new design into an improved product), and (f) reflecting and communicating the overall processes of designing and constructing. We argue that the application of, and reflection on, the STEM disciplinary content during the design phases is a critical component, in accord with the well-documented role disciplinary knowledge plays during design-based problem-solving (McKenna, 2014; Roth, Tobin & Ritchie, 2001; Wendell & Lee, 2010).

Furthermore, we maintain that the iterative nature of engineering design prompts students to reflect on their knowledge application as they revisit a phase in their efforts to optimise goal attainment. We use the term, *reflect*, in accord with Schon's (1983) notion of reflection-in-action, that is, students' reflections while undertaking engineering design processes (Wendell, Wright & Paugh, 2017). Furthermore, reflective workbook record-keeping tasks, as used in this study, have been shown to facilitate students' science learning (Wendell & Lee, 2010). As students transform their designs into a product, test its feasibility, reflect on the strengths and weaknesses, and subsequently redesign and reconstruct, they need to identify, understand, and apply core concepts and principles of the STEM disciplines (Lachapelle & Cunningham, 2014; Lewis, 2005). In other words, 'learning while designing' is being promoted (Crismond & Adams, 2012,

p. 744). For example, in checking that goal constraints are being met, students need to review their use of appropriate disciplinary knowledge such as how to stabilise a bridge structure taking into account the impact of forces. In identifying the strengths and weaknesses in their initial design, students might observe that they need to distribute the weight more effectively by adjusting the distance between their bridge's piers and by increasing the use of cross-bracing.

Design sketches further contribute to students' learning by helping them to develop and convey meaning and understanding about a given problem (Song & Agogino, 2004; Tversky & Suwa, 2009), as well as draw on and connect the targeted disciplines in creating and annotating their sketches. In line with Song and Agogino's (2004) perspective, we see a design sketch as including varied forms of displayed representations, where the main features of an object or situation are documented in attempts to 'give external definition to an imagined, or only half-imagined, suggestion for a design form' (p. 1). Design sketches are just one of multiple communication modes assisting problem solution, with the interaction of multiple modes considered essential in conveying meaning (English & King, 2017; Roth et al., 2001). Furthermore, design sketches can play a powerful role in knowledge scaffolding where students' application of disciplinary content is called for. Despite its contributions to learning, design sketching appears to lack the recognition required, often because of claims that younger students would rather experiment with materials instead (e.g. Welch & Lim, 2000) or lack the drawing skills needed (e.g. MacDonald & Gustafson, 2004). Primary school students' approaches to applying their STEM knowledge in planning and design sketching remain under researched.

Reflection and Scaffolding

The important role of students' reflections on their knowledge application as they solve an engineering design-based problem has been advocated in several studies (e.g. Capobianco et al., 2017; Cunningham, Lachapelle & Davis, 2018; Guzey et al., 2017; Moore et al., 2014b; Wendell & Lee, 2010). Engineering design provides repeated opportunities for students to reflect on their ideas and actions, to implement their learning, to test, and to reflect again, and to ultimately develop 'deep and lasting understanding' (Cunningham et al., 2018). McKenna's (2014) emphasis on interactions between 'the learner and the problem-solving environment' is particularly pertinent, where students learn from and about a problem, 'while continually reflecting on, and possibly reshaping, prior knowledge and experiences' (p. 232). In a similar vein, Reiser (2004) notes the challenges students face in science investigations, which involve what he terms the 'complementary processes of reflection and articulation' as students keep track of and assess their progress, review and refine their plans, and communicate their understanding as they progress (p. 277). Such opportunities are often not available to students in their regular mathematics or science activities but are clearly needed in any STEM investigations (Reiser, 2004).

Prompting students to identify, review, and document how they applied their disciplinary knowledge during problem solution has been shown to have a positive impact on student outcomes (Capobianco et al., 2017; Wendell & Lee, 2010). Knowledge scaffolding, involving both learner support and the facilitation of further learning, has been emphasised in McKenna's (2014) research on 'scaffolding of knowledge innovation' (p. 232), as well as in Reiser's (2004) work on 'scaffolding complex learning' involving structuring the problem-solving task and problematising the disciplinary content (p. 273).

Although scaffolding traditionally involves interactions between a teacher and learners, other forms involve students' interactions with curriculum materials (Wendell & Lee, 2010), with student workbooks and notebooks (Hertel, Cunningham & Kelly, 2017) and with various representations and artefacts (McKenna, 2014; Nathan et al., 2013; Sherin, Reiser & Edelson, 2004). While the present study incorporated supportive teacher and student interactions, a key form of knowledge scaffolding involved content-based questions and design challenges in student workbooks, together with associated group interactions (as discussed in the "Methods" section).

Although workbooks and notebooks can facilitate record-keeping, shared thinking, understanding, and reflective practices, ways in which these documents can support students' learning have received limited attention (Hertel et al., 2017). Further study is needed on these less traditional forms of scaffolding, especially given the importance of Reiser's (2004) 'problematizing' mechanism of scaffolding, which fosters students' understanding of key core disciplinary knowledge and encourages continued engagement with a complex problem. Problem solving then becomes a more productive learning opportunity and prompts learners to consider issues that they might not otherwise address (McKenna, 2014).

Methods

Participants

We report on five sixth-grade classes from two independent girls' schools in a large Australian city (mean age, 11 years 6 months). One independent school (four classes; $N = 82$) was situated in the middle of the city while the other independent school, with only one sixth-grade class ($N = 25$), was in a suburban area. Students were generally drawn from middle socioeconomic homes. The students had participated in the study since their fourth grade.

Across the 3 years of the study, we also involved practising engineers from different fields, as well as postgraduate engineering students from our university.

Previous Experiences

In the first year of the study (fourth grade), the students explored different fields of engineering, the roles engineers play in society, and how engineering is improving their local community. Across the 3 years, students completed several sets of engineering-based problem activities that drew on their STEM curriculum and required the application of basic engineering design processes. These activities included 'Tumbling Towers' (tower building with minimal materials), an aerospace activity, a 'medical mission' problem, building an optical instrument, a biomimicry investigation, and constructing earthquake proof buildings.

Bridge Building Activities

Bridge building is a common engineering activity for school students (e.g. Carroll, 1997). It is both appealing and flexible in its structure, lending itself to a variety of construction materials and approaches. The present set of activities addressed core goals and themes of the teachers' existing curricula in mathematics, science, and design technology. Table 1 displays the basic STEM disciplinary content that was involved in the bridge building activities. While some of this content knowledge can apply to more than one discipline (e.g. estimation and measurement in both mathematics and science), the content is listed according to the primary discipline in which it is taught. The level of STEM content understanding expected of the students was in line with the requirements of the Australian Curriculum.

Preliminary Activities. A number of preliminary activities were designed to scaffold the development of the students' foundational STEM knowledge for working the main problem. This introductory learning included the following:

(a) Reading of the story book, *Engibear's Bridge* (King & Johnson, 2014), which is the second in a series of books introducing students to engineering and engineering design processes, together with related mathematics, science, and technology concepts.
(b) Identifying and comparing the various features of the basic bridge types, namely, beam, truss, cantilever, and suspension, together with examining well-known global examples.
(c) Identifying shapes comprising the bridge structures and their roles in supporting the bridge (e.g. triangular trusses can be added to support a beam bridge).
(d) Developing a basic understanding of the forces of compression and tension, identifying how these forces act on the different bridge types, and the roles of these forces. Students had been introduced to the notion of forces in their fourth grade. This basic understanding was revisited and consolidated prior to the students undertaking the bridge activity.

Table 1 STEM disciplinary content of the bridge building activities

Science	Engineering and technology	Mathematics
Develop a basic understanding of forces including tension and compression Identify forces acting on different bridge types Understand how different bridge types support a load Understand materials and properties	Engage in engineering design processes Generate, develop, communicate, and document design ideas and processes Recognise basic bridge types (e.g. beam, arch), bridge support structures (e.g. trusses, beams, cross-bracing), and how these structures enhance stability and strength	Apply estimation and measurement skills Apply spatial reasoning in recognising and working with different 2-D and 3-D shapes Communicate design details through 2-D and 3-D representations Apply computational skills Understand basic notion of scale

(e) Reviewing basic engineering design processes and building on students' previous engineering activities.

Student Workbooks and Teacher Guides

As previously noted, student workbooks facilitated students' reflections on their learning and scaffolded their learning. Our development of the student workbooks and teacher guides aligns with Hertel et al.'s (2017, p. 1201) approach where these documents structured teachers' lessons, provided reference for student decision-making, prompted students to reflect on their actions, and supported 'epistemic practices of engineering' (e.g. 'synthesise and reflect on engineering design', record testing data for evaluating designs and improving structures, and provide a record for communicating including class reporting and sharing). The workbooks also held the groups accountable to their plans, thus supporting the development of engineering design practice.

The Bridge Problem

Prior to designing and building their bridges, students completed a number of questions in their workbooks including the type of bridge they planned to build and why, the shapes they intended using for their bridge and why, the proposed height and width of their bridge, and how they would make their bridge strong. Next, students were to sketch and label some draft designs, and then experiment with the given materials in exploring different construction methods. Students were able to modify the materials as they wished (i.e. cut, tear, etc.). Discussion of possible designs within their groups followed, taking into account the quantity of materials to be used. In completing their designs, students were to draw and label their first design (including identifying shapes used, bridge measurements, and materials used).

Students then began testing the load capacity of their first bridge design by placing one 500 g weight on top of the bridge (smaller weights were also provided). Students were to observe, describe, and record what happened when the first weight was placed on the bridge. They continued placing extra weights on top of the bridge until maximum load capacity was reached. Again, the students were to observe, describe, and record what happened when the final weight was placed on the bridge. They were also asked what they had learned about their bridge from the test, including any mathematics and science they applied.

Prior to undertaking a redesign in an effort to increase their bridge's load capacity, students recorded how they planned to improve their design and how their proposed changes would accomplish this. Students then repeated the design process and constructed a second bridge, recording their observations as indicated above. On completion of their bridge constructions, the students recorded reflections on their learning. These included what they considered to be their better design (initial design or redesign) and an explanation of 'how you were using your maths and science ideas today for the design of your bridge'. At the conclusion of the activities, each student group presented a report to their class peers. They were to describe their bridge designs and construction including its type, the shapes used, how the bridge withstood capacity testing, the quantities of materials used, and which design they considered their best and why. Preparing their class reports prompted students to reflect on their engineering designs and processes, including their design sketches.

Follow-up activities (not reported here) addressed science topics within the curriculum including physical and chemical changes to a bridge (e.g. weather affecting a bridge's stability, chemical reactions over time leading to steel rusting and concrete corrosion).

Implementation. The Bridge Problem (see Supplementary Material) was implemented over two, 1-day sessions of 3.5 h. Each student was presented with a workbook in which they recorded their own responses to the questions described above. Although working in groups, students were to document their own ideas.

The class teachers implemented all of the activities, while the researchers were in attendance. We conducted briefing and debriefing sessions with the teachers to introduce them to the activities and to provide opportunities to review the students' developments. The teachers were advised not to intervene directly in the students' working. Rather, learning was to be facilitated where necessary, such as responding to a student's query by posing a thought-provoking question in return. The engineers also observed the students undertake the activities but were asked to not directly influence the students' responses.

Data Collection and Analysis

Several sources of data collection were undertaken including audio and video recordings of the focus groups' interactions in designing and building their bridges, as well as whole class discussions. Focus groups comprised three, occasionally four, students of mixed achievement levels, selected on the basis of their ability to converse and work together. Students' constructions were photographed, and their workbooks scanned.

Both qualitative and basic quantitative (frequency distributions) analyses of the data were undertaken. The first author commenced with a form of open coding (Strauss & Corbin, 1998) after repeatedly studying the students' workbook responses and design sketches to identify and code evidence of core disciplinary content. The codes were checked by the second and third authors, and then checked again by the first author. Any inconsistencies in codes assigned were refined through mutual agreement, and the results summarised (Creswell, 2002). Descriptions of the codes used in addressing the research questions are presented with the results.

The analyses of the focus group and whole class transcripts adopted the form of iterative refinement cycles for in-depth evidence of students' learning (Lesh & Lehrer, 2000). Through repeated analyses of the transcripts, we identified examples of focus group students applying engineering design processes, together with the application of STEM disciplinary knowledge in developing their bridges (as indicated in Table 1).

Results

In reporting our findings, we consider a selection of the students' workbook responses, their design sketches, and two of the focus group discussions during their bridge constructions. In doing so, we revisit each of our research questions in turn. We consider individual student responses rather than group responses, as group members were to record their own ideas and these were not always the same within a group.

Research Question 1 (a) How Did Students Apply Their STEM Knowledge as Evident in Their Preliminary Planning and Design Sketch Annotations?

Preliminary Planning. We consider two core preliminary planning questions asked of the students, namely, the *type of bridge* they planned to build and *why*, and how they intended making their bridge sufficiently *strong to support a load*. For the former, we coded students' responses as follows (in addition to no response or an irrelevant response): (1) articulated bridge type but gave no justification for selection; (2) selected a bridge type because it met the problem requirements or part thereof, for example, 'It's high enough to allow boats through', 'it has supporters'; and (3) selected a particular bridge type and referred to (a) its strength and/or stability, its minimal use of materials, and/or (b) an engineering principle that strengthens the structure, or inclusion of triangles 'because they're strong'.

For their bridge type selections and justifications, students chose a range of types, with several students planning to use a combination, an unexpected finding (Table 2). The most common type was the truss/cantilever, followed by the beam bridge and its combinations.

Students' justifications for their chosen bridge types indicated that they were aware of the importance of stability, load capacity, and structural support. Sixty-three percent of the students ($N = 107$) gave explanations with reference to disciplinary features such as stability and how the use of triangular shapes or other structural components made the structure stronger. Responses included, '... a truss bridge because it is capable of standing with weight and is supported by trusses on the sides'; 'We are making a cantilever bridge because we think triangles would be strong and great for our design'; 'Truss, strong and stable with the ability to withstand most environmental impacts'; and 'Beam bridge because it is compact and supportive'. Thirty-one percent indicated that they chose the particular bridge type because it met the problem requirements, such as 'It's high enough to allow boats through' and 'Suspension bridge because we think it will hold well'. The remaining 6% of students simply articulated the type/s of bridge but did not explain why they planned to use it.

For the latter question, (making the bridge sufficiently strong), we coded students' responses according to their identification of mathematical shapes and engineering principles that strengthen a bridge. In addition to an irrelevant or no response, we coded

Table 2 Frequencies (%) of planned bridge types

Bridge type	B	T/C	A	S	B & T	B and A	T and S	S and B	T and A	A and S	A and C	C, A, and T
Freq.	26	30	12	8	7	2	3	3	1	3	5	1

N = 107

B beam, *T*/*C* truss/cantilever, *A* arch, *S* suspension the responses as (1) only gave reference to the use, quality or quantity of materials, with no indication of how these would make the bridge strong; (2) referred to making their structure strong through the use of particular mathematical shapes (e.g. cylinders, triangles, triangle trusses) but did not explain how the use of the shapes would strengthen the structure. The response did not indicate how specific engineering concepts and/or principles would strengthen the bridge; (3) referred to an appropriate use of one or more engineering concepts/principles, and/or how particular combinations of shapes would increase support/strength.

Just over half of the students (59%, *n* = 107) gave explanations that referred to how applying particular engineering, mathematics, or science knowledge would enhance their bridge's strength. Examples of responses included, 'We will use sticky tape as suspenders which will support the beam and also transfer the forces'; 'Arch and using a cantilever to support the walkway. The suspenders will provide balance with the tension'; 'We will use lots of cross-bracing and we will also use supporters from pier to pier'; 'With the way we weave the bridge to make the road strong and the cantilevers under the bridge'; and 'In our rectangular prism there will be some smaller cylinders and piers underneath for more support'.

Twenty-nine percent identified the use of particular materials or shapes, such as cylinders or triangles, and occasionally mentioned engineering principles, but did not articulate how these would enhance strength. For example, these students responded, 'By adding triangles, squares, and cylinders'; 'We will make the structure strong by making squares and triangles, which are the strongest shapes to build with'; and 'Fold pieces of paper and make support'. The remaining students either did not attempt the question or gave an incomplete or basic answer, such as 'We will make it very strong by using paper and sticky tape'.

Sketch Annotations. In coding and analysing the students' sketches in designing and redesigning their bridges, we adopted Song and Agogino's (2004) notion of annotation, namely, a 'type of support notation' metric, which includes 'labels, lists, narratives, dimensions, and calculations' (p. 2). To code each student's first and second design sketches, we used a simple matrix comprising the following types of annotations: (a) an appropriate clearance height (i.e. a minimum of 15 cm); (b) an appropriate span (i.e. a minimum of 21 cm between piers); (c) labelling of shapes used; (d) inclusion of bridge measurements; (e) inclusion of engineering principles (e.g. cross-bracing, trusses); (f) labelling of structural features (e.g. deck, pylon, piers); (g) labelling of materials used; and (h) inclusion of quantities of materials used. Using a simple frequency count of each annotation type on each student's design sketches, it was found that over half of the students met the problem constraints of minimum clearance (65% of responses, *n* = 107) and minimum span (65%).

Annotations of measurements (77%) and quantities of materials used (85%) were more frequent, while the correct labelling of shapes (28% of responses) and the labelling of materials used such as the paper (26%) were limited. In contrast, annotations indicating engineering concepts and principles (e.g. cross-bracing), as well as structural components, such as deck and pylons, were featured more frequently (31 and 41%, respectively), collectively reflecting an application of engineering knowledge (Table 1). Figure 1 illustrates one student's design displaying mathematical and engineering features.

Students' annotations on their second designs were not as prevalent with respect to minimum clearance (65% of student responses for first design; 28%, second design; $n = 107$), minimum span (65% for first design; 27%, second design) the labelling of shapes (28% for first design; 18% second design), and the inclusion of measurements (77% for first design; 26% for second design). This reduction in annotation could possibly have been due to time constraints (coupled with some fatigue) towards the end of the activities, as well as a few groups' satisfaction with their first design, resulting in two groups not undertaking a redesign. Nevertheless, the students continued to display an application of engineering knowledge, with 34% (30% for first design) annotating engineering concepts and processes and 41% accurately labelling structural features on both designs. Only one student indicated the forces acting on their bridge in either design (Fig. 2, Supplementary Material), despite considerable time having been devoted to bridge forces in the preliminary sessions. This is perhaps not surprising, given the complexity of the concepts of tension and compression. The student group interactions, however, revealed a basic understanding of forces as illustrated in the next section.

Research Question 1 (b) How Did Students Apply Their STEM Knowledge as They Engaged in the Processes of Engineering Design?

In this section, we detail the interactions of two, randomly selected groups (Gwen's and Bella's, one from each school), as they designed, constructed, and redesigned their bridges. In analysing students' interactions as they worked in their groups, we looked for evidence of their application of the science, mathematics, and engineering knowledge components as displayed in Table 1.

Gwen's Group. This first group applied primarily engineering and mathematics, and occasionally science knowledge in designing and constructing their first bridge.

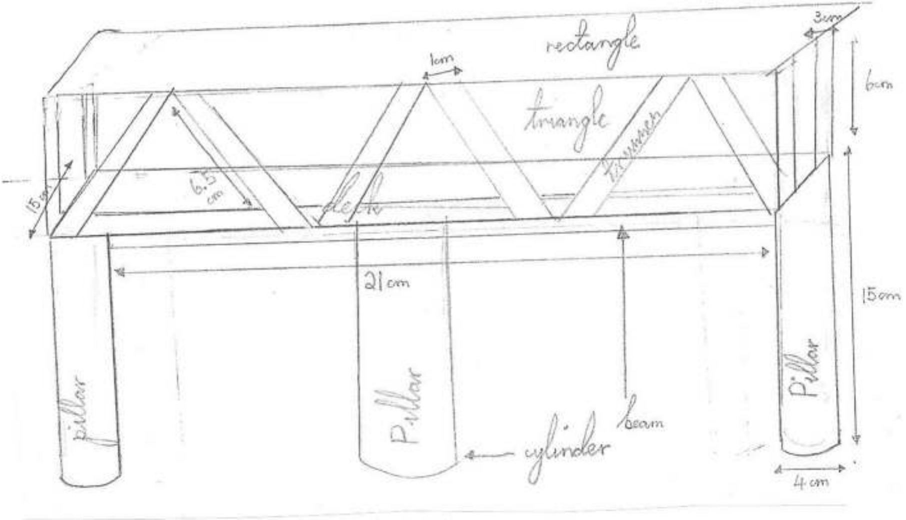

Fig. 1 Design sketch displaying mathematics and engineering features

Deciding on a beam bridge, Gwen's group brainstormed approaches to construction referring to the need to brace their bridge to increase stability, with Gwen commenting, '… just remember that the weights are going on top of it, if you only have the things in the corner they might … bend in the middle'. Carly agreed, 'So that's why I was thinking we should do trusses like somewhere in the middle'. Lilly reminded the group of the height constraint to enable boats to traverse, to which Gwen and Carly responded by explaining how the trusses were to be placed and how they will 'have this like big span; we have this like area in the middle'. As the group responded to questions in their workbooks, they noted that they had decided to build a beam bridge because 'it will be a stable design' but that they '… would use lots of supports'. In deciding on the height and width of their bridge, Gwen clarified terms for Carly explaining that the span refers to 'across' the bridge and 'pier to pier is this bit'.

On being asked about their planned construction, Gwen's group explained that a beam bridge would require the least amount of materials and that they expected it to be stable because of their use of trusses and cross-bracing: 'It's very stable underneath so we'll do it (the use of trusses) most of the way but we'll have a little gap so that a boat can travel through. And also, the cross-bracing helps support it a little bit so that it doesn't come caving in … also, if the bridge is too long then it will collapse in the middle, so we kind of need the cross-bracing to … support in that middle area'.

As the group drew their design, the members questioned one another as they tried to visualise their end-product. For example, their drawing of triangles to represent the trusses led to a debate about the difference between the two, which was clarified by one of the visiting engineers. As the group progressed, they repeatedly referred back to the problem constraints especially the need for a minimum height and width: 'But remember, Carly, we need the minimum ... the minimum clearance at the bridge centre'. Constraint checking continued as the group added cross-bracing. Bringing in their mathematical knowledge, the group grappled with how to roll their paper to maximise its strength, namely, along the width or length of the sheet, with Lilly commenting, 'Cause if we rolled it from this…the short end (rolled on the length so it's 21cm high), we'd make it thicker and it would be smaller'. The group kept an on-going record of the materials they had used ('How much sticky tape do you think? 3 [cm]? So that's 10 cm so far. So that's 20 cm for all of them [piers]. Hold on, hold on. Use as little [sticky tape] as you can').

When deciding on the number and placement of the piers, the group drew on each of their engineering, science, and mathematics knowledge bases in considering the forces that would act on the bridge, debating whether two or four piers were needed, and taking several measurements as they completed their first bridge: 'We have to make four of these [piers]… We can't just have one at each end because it will … this one will have too much pressure … and bend'. The debate continued because the group's annotated design only displayed two piers. On agreement to have four, the group ensured that they were all the same height and questioned whether they would be strong enough to hold any weight: '…. if it's standing like this and then the weights go on top it's going to collapse … that's why we've got to have cross-bracing across there [the deck]'. The group continued to record measurements as they progressed in their bridge construction, remaining cognizant of the quantity of materials they were using and the constraints of the problem: 'Try to make it [cross-bracing] as close to the top [of the deck] as possible cause we still need that [clearance]'. An interesting insight into the group's collaborations was evident as they reflected on their progress, '… we are doing well because … we put aside our differences and we are working'.

On moving to their redesign, the group reflected on the features of their first bridge, the mass it would hold (600 g), and how they would develop further the ideas they had shared in their first bridge. This reflection enabled them to apply their mathematics and engineering knowledge in increasing the strength and stability of their bridge: '… well we can double up a little bit so like put another one [cylinder] in there [inside existing pier] … and a twisty [paper cable] in there'. This was followed by cross-bracing, with Carly explaining when asked: 'We were thinking of doing a little more cross-bracing here [under the deck] and another one up here so it joins the columns more … because in our experiment, when we were testing it, it kind of bent a little bit [sagged in the middle], like it [the piers] turned out [outwards]. So we need to bring them [piers] closer together'. The group further explained how the cables ('twisty sticks') and the cross-bracing interacted to add stability and strength:

> Carly: Well it also matters about what we're calling the twisty sticks [paper cables] cause they're nice and tense and the cross-bracing kind of overlaps them and joins them to the paper [deck] so that it's tense.
>
> Gwen: So that if this one [paper cable in the cross-bracing] was to slip, that one [paper cable] will hold it back … cause they're joined.

Once again, the group frequently referred back to their redesign sketch as well as to the problem constraints: 'We have to put it [the bracing] as high as possible because boats can't get through'. 'We've got to make sure it [clearance] is 15 cm'.

Bella's Group. This group applied primarily mathematics and engineering knowledge in designing and constructing their first bridge. The group spent considerable time deciding on the type of bridge to build, with a truss and an arch being favoured as they sketched possible designs. The group wavered between an 'arch with bracing' and a truss with triangles '… cause triangles are strong'. The group drew on their knowledge of the Sydney Harbour Bridge as they continued sketching and discussing where to place piers and abutments. Bella suggested the group stop sketching and 'experiment'. The nature of the materials was of concern to the group as they lamented on why they were given paper and not cardboard or 'metal' that would be more durable. As Lucy experimented, she indicated that the paper could be strengthened by layering it and making a triangular prism. The group then experimented with an arch, taking a piece of paper and rolling it lengthways into a cylinder and then bending the shape. Bella, however, considered that they needed 'more of a triangle', to which Mia commented that 'we're aiming for an arch'. Returning to sketching their redesign, the group checked the problem constraints ('So how long does it have to be from pier to pier again?') and discussed whether their bridge would have 'four legs', whether they should 'make the legs pretty wide', and whether there should be 'one in the middle'. Drawing on their engineering and science knowledge, the group noted 'The main thing about the arch is that it transfers the weight'.

Linking their mathematics, science, and engineering knowledge, Bella's group spent substantial time experimenting and debating how to construct their arch bridge while ensuring the weight was distributed evenly. Bella questioned the use of sticky tape to attach the arch to the piers at either end, in preference to the additional use of paper to strengthen the piers. Her concern for using minimum materials to win the 'bridge challenge' appeared uppermost in her mind. Discussion followed on the number of piers ('legs') they should use to ensure the bridge was 'balanced'. One pier was dismissed as 'It's got all the weight on it …' and the need for distributing the weight by using three piers was stressed: '… the weight needs to be on this so that the arch can take the pressure'. Debating whether a pier could be placed under the middle of the beam, one member claimed that several bridges have such a pier and boats can still 'fit through'. Another member, however, alerted the group to the problem constraint of the distance from pier to pier.

The group's creation of a corner gusset to secure a pier to the beam revealed their application of mathematics and engineering knowledge. The group constructed a square ('a perfect square') and subsequently a right-angled triangle ('Fold it in half again … I did it [a corner gusset] … and we connect it to one of these [piers]'). Attaching an arch proved difficult however, with Bella noting that 'Our arch didn't help much' and Lilly commenting, 'We might need to develop that'. In observing that the arch 'does like nothing', Mia recommended adding 'a big piece down here so the arch can actually take the pressure' (pointing to the base of a pair of piers at one end of the bridge and referring to adding a strip of paper between the two piers to which the arch can also connect). Completing their bridge proved cumbersome as the group attempted to add substantial cross-bracing while also keeping track of their material usage. Ensuring the arch was stable and served its purpose, the group debated whether to add trusses or more corner gussets, but then decided on abutments:

> Lilly: Make this truss sort of thing underneath come right to the middle of the bridge and it could be like a cross …
>
> Mia: Yeah that was our original plan; one of each of the four pylon's one [gusset] was going into the middle … I think that would make it really stable. That was our original plan.

In reflecting on and assessing their first bridge construction prior to redesigning, the group considered 'balance' to be their main component to address ('… I think our main issue was balance 'cause it didn't buckle or anything, it just tipped … and it is still in perfect condition'). In sketching a redesign, Lilly argued that the problem was also one of 'load' ('…you could tell the first part of it was sagging') and suggested the need for more engineering principles to increase support: '… get supports to go right up to the middle (*signalling long corner gussets to connect piers to the middle of the deck*) … cause that will help … and it still serves like an arc effect … an arch'. Bella added that abutments were needed 'to balance everything', but Lilly suggested the use of '… a cantilever sort of design up into the middle ... that serves the same purpose as the arch … and then it takes the weight right down'. Keeping in mind the minimum height requirement, Lilly suggested making 'like a trapezoid' as she folded a previous angle corner gusset; however, Bella preferred the use of abutments. In returning to the suggestion to reduce their bridge height, Lilly alerted them to the minimum boat clearance height before cutting: 'No! You need to measure it first. Who knows, it might be 17 cm (taking the ruler and measuring height of the second pier). So that's 20 cm. Just cut it where the 2 cm part is'. Debate then followed on which engineering principal would be best to ensure support and stability, namely, cross-bracing the length of the bridge or adding corner gussets to all four piers to 'support the load in the middle … to stabilise it a bit more'. After final construction, the group's redesigned bridge proved more successful with the load capacity increasing to almost 1000 g.

In sum, both group examples show how students applied their disciplinary knowledge through using engineering concepts (e.g. stability, strength, cross-bracing, and trusses), science concepts (e.g. forces), and mathematics concepts (e.g. measurement and geometry) to design and build a paper bridge. The student-student interactions were important for eliciting the STEM knowledge during the construction process where the application of the STEM concepts occurred in a fluid and creative manner.

Research Question 2. What STEM Knowledge Was Evident in Students' Reflections on their Learning?

To answer this last question, we analysed the students' reflections as evident in their workbook responses with respect to (1) what they had learned from their initial bridge testing, (2) what they considered to be their better bridge design and why, and (3) how they applied their mathematics and science in their bridge designs and construction.

Learning from Initial Bridge Testing. In identifying what the students had learned from their initial bridge testing, we coded their responses as (1) a brief response, such as 'our bridge was unstable and a failure'; (2) a more detailed, relevant response where the student referred to material use (e.g. effects of paper), or to the importance of designing, or indicated that more support was needed, or that different shapes were required to strengthen the structure. The student did not, however, refer to any specific engineering principles or practices, nor indicated how these hindered or helped bridge construction; and (3) a comprehensive answer in which engineering principles were identified and explanations provided for how these assisted or hindered their bridge structures. For example, a response might state that the piers were not strong enough as there wasn't anything supporting them, or that 'with abutments, the bridge can hold a lot more weight'.

Nearly half of the students (48%, $n = 107$) provided a code 2 response that indicated knowledge of material use (science), the importance of designing before building (engineering); the need to increase support and stability, for example, through strengthening the piers (engineering) or through the use of particular shapes (mathematics); and the importance of cost effectiveness (mathematics). Examples of such responses included, 'Our bridge is extremely unstable because we had no strong shapes'; '… the piers weren't even, we used maths to measure the length'; and 'I learnt that the arch wasn't very strong with paper'. These students, however, did not, refer to learning about forces acting on the bridge (science) or to how particular engineering principles would improve their bridge.

In contrast, 24% of the students referred to their application of more specific engineering, science, and mathematics knowledge; they also indicated how this knowledge impacted on their bridge constructions (code 3 response). For example, 'We completely forgot about cross-bracing. There needs to be something holding the bridge in the middle'; 'Bracing both sides of the piers helped make the general bridge more stable'; 'If there is a force in the centre then the deck will bow'; and 'During the process of building we changed a lot of the measurements to ensure we had the strongest bridge possible. We also used paper that we twisted as cross-bracing because it was tense, strong and didn't bend easily'. Seventeen percent of the students indicated only briefly what they had learned from their bridge testing, with responses such as, 'We learnt that our bridge has to be safe and strong for pedestrians'.

Assessment of Better Design. Students' reflections on what they considered to be their better design and why were coded as (1) referred only to the bridge design enabling a greater load or being stronger or more stable; (2) referred to enabling a greater load and/or increased strength and/or increased stability, together with some supporting explanation such as material usage; and (3) provided a more detailed explanation of why the design enabled a greater load, increased strength and stability, and/or referred to engineering, mathematics, and science knowledge (e.g. additional support accommodated a greater load).

Code type 2 responses were the most common (46% of students). Examples included, 'Our best design was our second one because it was more stable than our first one, it was simple and easy to build although we used more paper and tape'; and 'Our first design was best because we managed to balance more weights on it compared to our second'. Only 15% of students provided a code 3 response such as 'Our first bridge because it has a cross-brace under the deck to support it and it stood on its own' and 'Our second one because we added more bracing near the piers and we also improved by 600 grams when we tested it the second time'. Only a brief response with no explanation was given by 29% of students (code 1), who simply indicated that their preferred design accommodated a greater load or was more stable or 'stronger' (e.g. 'The second design we did because it held more weight').

How Students Were Using Their Mathematics and Science Learning. Finally, students' reflections on how they used these two disciplines in undertaking their bridge building were coded in terms of the discipline identified and the explanation provided. Unfortunately, a little over a quarter of the students were either absent or did not respond to this third component of reflections. With respect to the discipline students mentioned in their learning, we coded their responses as (1) referred to mathematics only, (2) science only, and (3) both mathematics and science. For students who provided explanations for their discipline choices, we coded their responses as (1) reference was made to how one of the disciplines (maths or science) was used, with specific mention of core maths/science concepts. Responses in this category included those students who identified only maths or only science, as well as those who indicated both but only give an explanation for one of the disciplines. Responses coded as category (2) included an explanation for how both disciplines were applied, with specific mention of core concepts for each discipline.

Although we wished to determine how students reflected just on their use of mathematics and science, several students identified engineering concepts in their responses. Such responses were not coded as either mathematics or science, even though engineering draws on these disciplines. Interestingly, more students identified mathematics as the only discipline (45%), in contrast to science (3%), while 28% of students identified both. Forty-seven percent of students offered explanations that referred to one of the disciplines, while 26% referred to both in their explanations. Those students who referred to both mathematics and science in their explanations offered responses such as 'We were using mathematics when we were recording the data and amount of materials we used in the table. We used science when we were looking at the forces on the bridge' and 'I was using mainly maths today because when building the model bridge I had to write down the measurements of the bridge, had to keep tallies on the amount of pieces of paper and sticky tape and keep track of how many weights were on the bridge. We used science when looking at compression and tension involving bridges'. Others made a list indicating features of each discipline, such as the student who highlighted measuring in mathematics and tension and force in science. Another student identified mathematics as including 'angles for using them [sic] to sustain the support to keep it stable and not collapse' and science in 'using different techniques and forces'.

Discussion

The contributions of engineering-based experiences in the primary school have been well documented (e.g. Bagiati & Evangelou, 2015; Guzey et al., 2017; Moore et al., 2014a, b). Such contributions include developing students' appreciation and understanding of the roles of engineering in shaping our environment, and helping students contextualise their mathematics and science learning. Engineering-based experiences can also improve achievement, motivation, and problem-solving, yet are often ignored because of teachers' lack of confidence or knowledge in engineering (Crismond & Adams, 2012). Furthermore, attempts at integrating engineering within STEM curricula often do not meaningfully incorporate science and mathematics content resulting in engineering being misrepresented as just 'an iterative trial-and-error tinkering process' (Clough & Olson, 2016, p. 381).

In the present study, we attempted to avoid such pitfalls by incorporating engineering, mathematics, and science within a set of problem activities in which engineering design served to both link and scaffold students' disciplinary knowledge and application. The set of bridge building activities revealed elementary school students' capabilities in planning, designing, reflecting on, and redesigning paper bridges that could hold optimal loads within given constraints. Students' planning indicated they could justify their proposed bridge type/s, often a combination of types, by referring to their mathematics, science, and engineering understandings while at the same time remaining cognizant of the problem boundaries. For example, students justified their use of particular mathematical shapes together with engineering principles to increase their bridge's strength and stability.

Students' design sketches indicated an awareness of the problem constraints, an understanding of basic engineering principles, and an application of mathematics and science knowledge. It was disappointing that their annotations did not display more science concepts such as forces; however, a greater display of each STEM discipline appeared in the group interactions. In their collaborations, students displayed a knowledge of the strengths and weaknesses of the different bridge types and how the use of engineering and mathematical principles (e.g. paper cables inside piers and corner gussets) can mitigate the effects of forces. Such interactions served to scaffold students' learning as they questioned one another's claims, identified ways to improve on their designs and constructions, and modified and extended their respective knowledge bases. Specific questions in the students' workbooks facilitated these group interactions by prompting students to reflect on and assess their actions, we well as keep track of the disciplinary knowledge they were applying.

Students' reflections on their learning indicated an awareness of how they applied the respective STEM disciplines, with a greater application/awareness of mathematics apparent although reference to both mathematics and science was given by little over a quarter of students. Students' explanations of how this knowledge enhanced their actual designs were limited, although a number of students did not complete this reflection question. Nevertheless, our results indicate how 'explicit integration' of engineering (Guzey et al., 2017) within carefully scaffolded STEM activities can facilitate elementary school students' application of mathematics and science knowledge, and help connect these disciplines with engineering processes and understandings.

As previous studies have shown, if engineering is not strongly connected to the other STEM discipline/s, students simply focus on constructing an engineering-based product and tend to ignore the other STEM content (e.g. Nathan et al., 2013). Given that elementary school students rarely engage in engineering activities that require them to apply core science and mathematics concepts (English, 2016; Guzey et al., 2017), more research is needed on providing opportunities for such learning through engineering design. In particular, engaging students in the iterative phases of engineering design can serve the dual roles of scaffolding and guiding problem-solving. The importance of these iterations has been advocated as an effective means of developing a deeper understanding of STEM concepts in engineering learning contexts (Park et al., 2018). Such scaffolding, however, entails a 'delicate negotiation between providing support and continuing to engage learners actively in the process'; in other words, an 'optimum level of challenge for learners' needs to be maintained (Reisser, 2004, p. 275). Such negotiation remains a problematic issue for researchers investigating integrated STEM learning. Providing just enough support to ease 'conceptual caps' (Wendell & Lee, 2010, p. 598) that might stall progress in younger learners, and presenting adequate question prompts that propel students through the design and construction processes, can alleviate noted difficulties in disciplinary learning in STEM-integrated experiences.

In line with Reiser's (e.g. 2004) and McKenna's (2014) work on knowledge reflection and scaffolding, we advocate for more research on this delicate balance between learning facilitation and learner independence in STEM education in elementary schools. Through carefully structured student workbook questions and prompts, we incorporated opportunities for students to identify and reflect on the disciplinary content they were applying during problem solution, and on how this knowledge informed their design and construction of their bridges. With the inclusion of a redesign and reconstruct phase, students were afforded further opportunities to review how they applied STEM ideas in their initial designs and how they could adapt or extend this knowledge in creating an improved bridge. To this end, Reiser's dual approach of providing required task structure and problematising core disciplinary content is worthy of further study (McKenna, 2014). Reiser's task structuring, similar to the form adopted in this study, guides or prompts learners through selected solution components (e.g. preplanning questions, use of design processes, design sketching), while problematizing alerts students to core disciplinary constructs, encourages them to tackle complex solutions in different ways, and overall, makes the learning more productive for the students. Ultimately, such STEM learning should lead to the development of what McKenna (2014) refers to as 'adaptive expertise' (p. 232), applying fluidly and innovatively what one learns in the context of design to new problem situations.

Limitations

A number of limitations are worth noting. First, given that the students were from single-sex, non-state schools, the inclusion of a broader cross-section of mixed gender schools would enrich the present findings. Second, science concepts pertaining to forces were not strongly evident in the students' written responses even though we devoted time to exploring bridge forces with the classes prior to their bridge design and construction. This finding highlights the need for further scaffolding to prompt students to utilise both their science and mathematics knowledge in design sketching and bridge construction. Lastly, the decline in annotations on the redesign sketches could have been due not only to time limitations and fatigue in some cases but also to some satisfaction with first designs and hence less enthusiasm for undertaking a redesign.

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