Technology-supported Engineering Design and Problem Solving for Elementary Students

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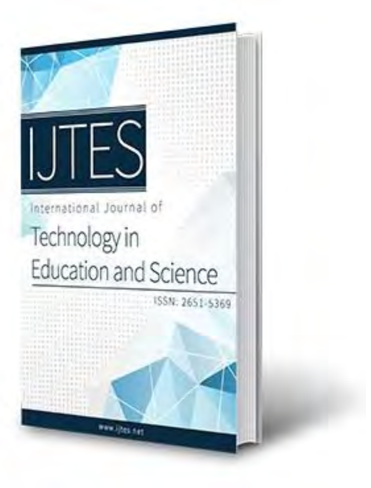

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Abstract

This study investigated the technologies and tools used to support upper-level elementary students' engineering design and problem-solving activities in a bridge design and building challenge. The study was conducted in an eight-week after-school program with a total of 36 4th to 6th grade students in small groups of four to six students. Analysis of students' group work based on video recordings revealed the use of a variety of technologies and tools. The results show that the use of technology was engaging and critical for helping students solve the engineering design problem and complete the design challenge. The use of disciplinary tools such as shake tables which are typically used by professionals also allowed students to perform certain tasks like professional engineers. Student focus group interviews showed students enjoyed the use of various technologies and tools during the design challenge. The study has implications for using technology to support K-12 students' engineering design and problem-solving activities, which include the authentic use of technologies and tools can transform learning and support critical problem solving and design thinking. The study also provides an example for instructors on how to use various technologies to engage and motivate students in hands-on engineering design tasks.

Introduction

Educational technology refers to a variety of tools, modes of content delivery and presentation with the help of technology, and strategies for using technology (Yang & Baldwin, 2020). Technology, however, is more than just a tool; it is a transformational process that can engage students and enrich their learning experiences (Nelson et al., 2009; Polly, 2014). As advances in technology occur, there are consequently new opportunities to improve teaching and facilitate learning in different and innovative ways. For example, student-centered learning approaches (e.g., constructivism, social learning) can be supported with computer simulations and virtual environments in science and engineering education (Yang & Baldwin, 2020). Further, learning experiences can be enriched using immersive and interactive technology, such as simulations and virtual reality, to facilitate learning multiple subjects at the same time. Technology can also bring remote subject content experts into the classroom to make up for the potential lack of content knowledge by an instructor or facilitator (Lunce, 2006; Smith & Mader, 2016).

However, merely providing students or instructors with access to technology or simply including it within a content area is often ineffective (Ertmer et al., 2012). Instructors can use technology superficially, or in ways that simply reinforce traditional practices (Cuban et al., 2001). Moreover, simply making technology available does not address the subtler yet challenging obstacle of intrinsic instructor beliefs about technology that can hinder its use (Ertmer et al., 2012). Kompar (2018) also highlighted that instructors may use a technology or tool for the sake of novelty which is similarly ineffective. Rather, technology needs to be focused on learning and integrated into learning processes in order for it to have a meaningful impact on learning outcomes, and which enables students to research, explore, design and experiment with content and/or learning tasks. Nevertheless, making technology integral to a curriculum and learning therein is often a complex and difficult challenge facing educators. This challenge also manifests itself differently across disciplines since each subject has its own unique contexts, making technology easier or more difficult to integrate in certain subjects.

In learning environments that are centered on engineering design, it can be difficult to use technology effectively since problem-solving activities are demanding in nature- requiring analytical skills and domain knowledge, as well as knowledge and expertise related to a given technology. Compounding this difficulty is the creativity required to solve complex problems. In the field of Engineering, engineering design refers to the steps that practitioners take to create a functional product (e.g., a bridge) or process (e.g., programming routine). It consists of (a) defining and identifying a problem; (b) developing possible solutions; (c) designing and testing prototypes; and (d) making revisions (Chabalengula & Mumba, 2017). Integrating engineering design into science education has been shown to improve student learning in science, technology, engineering and mathematics (STEM) subjects at both the elementary (Wendell & Lee, 2010) and high school level (Apedoe et al., 2008). Integrating engineering into elementary education can also promote technological literacy for students (Sun & Strobel, 2013). Nevertheless, despite the potential benefits of engineering design on student learning, it is difficult to implement in classrooms due to a lack of instructor expertise, as well as time constraints (Sun & Strobel, 2013). Modern advancements in various technologies, however, present viable solutions for facilitating and implementing engineering design, holding great promise for engaging students in inquiry and problem solving, which are essential in the engineering design processes (Krajcik et al., 2000; Kim, Park, & Tjoe, 2021). In this paper we present the results of how various technologies were used to support students' problem-solving and design activities in a bridge building challenge with upper elementary students.

Literature Review

Using Technology to Support Learning

Educational technology advocates believe that it can improve learning and help better prepare students for the 21st century (Garrison & Akyol, 2009). A notable advantage of educational technology is that it can provide unique affordances for promoting problem-solving and critical thinking. A report from the National Resource Council (NRC) (2014) explored the potential for using technology to provide learning solutions that are creative and conducive to meaningful learning. The report promoted using real-world contexts, solving real-world problems, analyzing and visualizing data, and ultimately reflecting and revising solutions to problems. Not only the US but also countries around the world have increasingly emphasized and promoted the integration of technologies in classrooms (Kim et al., 2021). Technology can also help alleviate cognitive overload when problem-solving by visually integrating information into a single image, ultimately reducing the amount of information processing required. Additionally, using technology to create an authentic learning environment helps students experience the challenges and complexity that are intrinsic to real-world problem solving (NRC, 2014). For example, Lego Mindstorms EV3 can be used to teach coding and programming in problem-solving tasks (Afari & Khine, 2016; Korkmaz, 2016) which students can then apply to their own environments.

In The Children's Machine, Papert (1993) discussed his collaboration with Lego on an invention that would eventually help create the first line of robotics kits aimed at facilitating self-directed learning in children. Such technology allows students to have more options and flexibility in working with physical objects and materials during their learning. For example, students can code and program using hybrid "screen-based and tangible programming languages" (Bers, 2010, p. 13) that blend tactile objects in the real world and programming syntax for young learners. Moreover, technology can help students use problem solving skills and serve as an instrument for students to express their thoughts and ideas in different and creative ways (Warschauer & Turbee, 1996). Some examples of this include the Augmented Reality and Interactive Storytelling (ARIS) platform, which was designed around a narrative metaphor (i.e., storytelling) for coding (Litts et al., 2020), or virtual environment interactions (VEnvI) that combined physical movement and programming with motion capture software (Dailey et al., 2015). Although technology can be a great tool for addressing challenges in teaching and learning such as moving classrooms away from lecture-centered instruction to inquiry-oriented ones (Culp et al., 2005), the use of technology needs to be carefully planned and implemented to achieve the intended objectives. Further, educational technology can be used at varying degrees of integration into a learning environment, and to different levels of effect (Cuban et al., 2001).

There has been increasing interest in studying technology-supported learning or learning environments that are often referred to by numerous terms such as e-learning, web-based learning, or internet learning environments (Gupta & Fisher, 2012). Technology supported learning can help learners develop knowledge and skills that, although attainable in conventional means, can be achieved in a more efficient manner (Mayer, 2005), and understanding the relationships between the affordances that technologies offer and learning environments is critical for pedagogical shifts to occur (Koehler et al., 2014).

Over the last 30 years, technology-supported learning environments have evolved from static, two-dimensional delivery (i.e.., websites and course management systems [CMS]) to dynamic, immersive environments in varying capacities (Huang et al., 2019). Educational technology can move beyond merely sustaining traditional educational practices in digital form (Cuban et al., 2001) or merely augmenting them with functional improvements (Hamilton et al., 2016), ultimately enabling teaching and learning to be transformed in meaningful ways such as how augmented and virtual reality can be used to support learning environments. Another area where technology supports learning is with the use of disciplinary tools or devices that are used by professionals in their respective fields. The use of such tools represents not only technology for educational purposes (i.e., educational technology), but authentic learning avenues as well.

Disciplinary Tools and Devices

Disciplinary tools or devices (i.e., the tools of the trade) refer to tools that can provide students with authentic, hands-on learning experiences in the same way that working professionals in the field actually use. For example, using CAD software to design prototypes and then using a 3D printer to fabricate and test them. These tools or devices can allow learners to practice and carry out a task like professionals normally do. Such disciplinary tools or devices can be used to help students test out their ideas by manipulating simulated or real data (Hsu et al., 2017). For example, a computer-based scientific modeling system that uses real data to investigate the effect of different variables on air quality (Wu, 2010) provides learners the opportunity to experience the scientific processes of defining and solving a problem like scientists at work. However, fewer studies have examined how disciplinary tools or devices that professional engineers use can support elementary students in their problem solving via hands-on engineering design activities.

For example, Jones et al. (2011) used a computer simulation program in a science course to engage pre-service teachers in scientific inquiry. In one of the learning activities, the pre-service teachers were required to use the simulation program to design a habitable planet by selecting various elements (e.g., type of star, distance from the star, etc.) available in the program. After the initial design task, they could get immediate feedback from the program, which facilitated subsequent iterations and design improvements. These types of computer-supported activities engaged the learners in the processes of questioning, predicting, reasoning, and more importantly, offered an opportunity to explore a planet which otherwise is not possible. The findings suggested that those pre-service teachers had a positive attitude toward technology-supported activities and wanted to include similar activities in their own classrooms once they started teaching (Jones et al., 2011). However, it is not clear how the effectiveness or engagement of such activities and tools translate into different learning environments, or with younger learners. For example, Chien and Chu (2018) found learning differences between college and high school students' use of 3D-printers and automotive designs where the undergraduate students performed better than their high school counterparts even though the same tools were available to all learners.

In another study by Schwarz and White (2005) with middle school students, a modeling program was used to help develop students’ inquiry skills for approximately 45 minutes per day for 10.5 weeks. The modeling allowed students to choose a set of alternative rules for force and motion to test and investigate the theories which they believed to govern the real world. After selecting alternative rules, the students were asked to provide explanations to justify their choices. The study findings suggested a significant improvement in students’ understanding of the modeling process, inquiry skills, and physics knowledge. Working with simulations, such as the manipulation of data on a computer, can assist students in making sense of the data, and enables them to build arguments based on evidence (Hsu et al. 2017), however these tasks also presuppose a certain knowledge and skill set that differs from that of elementary students. In summary, the use of disciplinary tools to support learning activities offers students ample opportunities to experience authentic scientific, problem-solving, and reasoning processes. However, research is lacking when it comes to disciplinary-tool usage for elementary school aged students and the engineering design process and related activities.

Technology-Supported Engineering Design

Roll and Wylie (2016) have suggested that over the next 25 years in education, technology supported education should see a focus on the evolutionary changes in classroom practices, teaching methods, and the diversification of technology, as well as revolutionary ones where technology can affect and transform students' lives directly, and are inclusive of their communities and cultures at large. The integration of engineering design in K-12 science instruction is indicative of a growing paradigm shift that has been accentuated in several documents (e.g., NRC, 2013; NGSS Lead States, 2013). These documents aim to better prepare students to meet the challenges and needs of increasingly technological societies. Engineering design activities offer the promise of enhanced critical thinking, problem solving, creativity, and authentic contexts to practice and apply various STEM subjects in one setting (Li et al., 2016; McNeill et al., 2016) and foster authentic environments for students to both learn and apply technology. Technology, ultimately, has dual purposes: to enable new and different ways of learning, and to assist students to solve problems. In engineering design, this can manifest by enabling constructivist learning approaches or by simulating multiple design solutions to a given problem.

As modern technology has become ubiquitous, technology-supported engineering design has become popular in classrooms (English et al., 2012; Zhou et al., 2017). For example, a wind tunnel (an engineering device) allows students to test the performance of their prototypes of an airplane design. Chien and Chu (2018) investigated the effect of using 3D-printers to support students' engineering design activities in a CO2-car engineering design curriculum. The study found that the use of 3D-printers helped high school students, college engineering students, and college design students in their engineering design activities. There were significant differences in creativity, forecast accuracy, race outcomes, and learning outcomes between the students who used 3D-printers and those who did not use them. The study also found that the undergraduate participants generally performed better than their high school counterparts due to prior knowledge and experience with design. In another study, Gilbuena et al. (2012) studied the benefit of a "Virtual Chemical Vapor Deposition (CVD) Laboratory" in five high schools. The virtual laboratory was able to simulate a manufacturing process in the integrated circuits industry and provided students multiple opportunities to develop and refine solutions to the engineering design processes used in manufacturing. The lab highly motivated the students due to its authenticity and was able to promote students' cognition development via knowledge integration, hands-on engineering design activities, and reflections. Such activities are emblematic of engineering design since these types of challenges (e.g., car design, chemical simulations) typically require a process of analysis, testing, and iteration to be solved. Moreover, as challenges, they foster collaboration over competition (Householder & Hailey, 2012).

Nevertheless, despite the benefits of technology-supported engineering design in students, there is little research on engineering design activities that are supported by technology, especially with younger learners. In general, technologies are often used as a tool (e.g., collecting assignments electronically) instead of being purposefully integrated into the learning process. Meaningfully integrating technology requires a shift beyond merely serving a supporting role in learning. Technology used solely as a supporting tool is found in the majority of technology-supported learning environments (Cantrell & Knudson, 2006; Capobianco & Lehman, 2010; Cuban et al., 2001; Ertmer et al., 2012; Williams et al., 2017). To achieve the potential of technology, technologies should be integrated meaningfully into all learning activities. The purpose of this study was to investigate how technology was used to support elementary student activities during a bridge design challenge. The study was guided by the following research questions:

1. How does technology support students' bridge design and building activities in an engineering design challenge?
2. How does technology help engage students during the engineering design and problem-solving process?

Context of Current Study

A STEM+Computing curriculum was designed as one part of a larger study investigating the integration of computational thinking (CT) with upper elementary school students (Yang et al., 2021). CT goes beyond programming and is a fundamental skill for everyone to solve complex problems (Lee et al., 2011). The STEM+Computing curriculum infuses the four disciplines of science, technology, engineering, and mathematics and CT through hands-on problem-solving (Yang et al., 2018). This study was grounded in the engineering design process (Figure 1) which is a seven-step problem-solving approach for addressing real-world, open-ended problems. This design approach applied within the STEM+Computing curriculum tasked students with building earthquake-resistant bridges, which was guided by project-based learning (PBL) approach (BIE, 2017) for a river in the community where the students resided. Starting out the design process was a driving question - How can we design an earthquake resistant bridge for the ABC (pseudonym) River? The learning and design process was facilitated by technologies such as smartboards and Chromebooks.

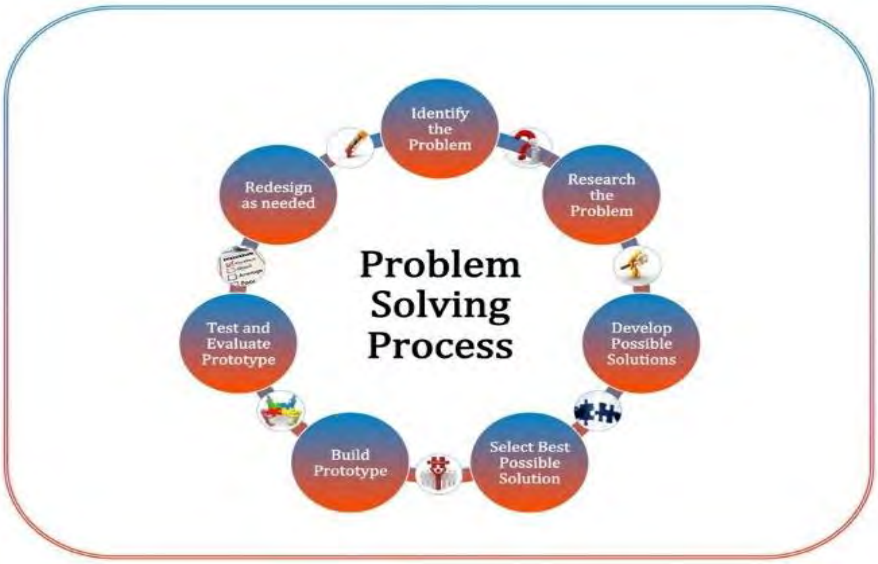

Figure 1. The Engineering Design Process

The bridge design project was aimed to invigorate students to learn and integrate CT and STEM knowledge to solve the driving question. In the building bridges project, students designed and built bridges using the K'NEX building kit. The project had a culminating design challenge to showcase student-made bridges at the end of the project. The curriculum was implemented with 4th to 6th grade students in an afterschool setting in two 90-minute sessions per week over an eight weeks period for two semesters. Each semester, the students were assigned into groups of four to six by the session's teachers (the project's facilitators). The project's subject matter experts (members of the research team) from a local university were also present during the implementation each semester

Method

Case Study

Case study has been extensively used in educational research to study individuals and the activities that take place within the boundaries of a real-life setting (Merriam, 2009) or real-world context, especially when the boundaries between phenomenon and context are not clearly evident" (Yin, 2014, p. 18). The "case" in this study was defined as students participating in an informal afterschool STEM+Computing education program (Yang et al., 2021) for two consecutive semesters, where the units of analysis and observation were the groups of students. Participants A total of 36 students from two elementary schools in the Northwest U.S. participated in the project, which were video recorded. General characteristics of the participants are presented in Table 1. 83% of the participants had never used K'NEX to build a bridge previously.

Table 1. Participant Demographics

Participants		Spring Implementation School A n=18	Fall Implementation School B n=18	Total n=36
Gender	Male	10 (55.5%)	14 (77.7%)	24 (67%)
	Female	8 (44.5%	4 (22.3%)	12 (33%)
Grade Level	Fourth	9 (50%)	6 (33%)	15 (41.5%)
	Fifth	6 (33%)	12 (67%)	18 (50%)
	Sixth	3 (17%)	0 (0%)	3 (8.5%)

Data Collection

Data was collected in two formats: videotaped sessions of the STEM+Computing curriculum implementations, and focus group interviews with participants at the end of each implementation. Videotaping the sessions allowed the researchers to later watch and identify technology usage throughout the students' bridge design and building activities.

Data Analysis: Videos and Focus Group Interviews

The researchers watched the video recordings and identified all the technology and tools used during the curriculum implementation. The technologies and tools that students used were then mapped with each stage in the problem-solving process (see Figure 1) in order to present how students engaged with the tools and technologies and how the technologies and tools supported the engineering design and problem-solving process.

The coding of this portion of the video recordings was an a priori approach using the problem-solving process (see Figure 1). The results are presented later in Table 4.

In the focus group interviews, 12 (out of 13) students from the spring semester's implementation and four (out of 12) students in the fall semester were interviewed at the end of the implementation. Students were asked about their experiences in the bridge design challenge and what they liked and/or disliked about the whole problem-solving and design process with the use of various technologies. The interviews were later transcribed, and placed into an NVivo file for coding. Data were analyzed by "identifying, analyzing and reporting patterns (themes) within data" (Braun & Clarke, 2006, p. 79). First, we used ideas in the data as the units of analysis, and then coded transcripts for individual ideas with attention to how technology supported the activities, and how students engaged with the different tools. Ultimately, the researchers grouped similar ideas together to create categories and then grouped relevant categories to create themes which represented important and patterned responses in the data set (Braun & Clarke, 2006). One faculty led the data analysis with two doctoral-level research assistants helping the whole process. All three researchers first independently coded the video recordings using the problem-solving process (Figure 1) and the focus group interview transcripts. The percentage of agreement was more than 90%, which was considered high and acceptable. The researchers then discussed any codes where the thoughts diverged until consensus was reached, and the results of analysis are presented in Tables 3 and 5.

Results

Technology-supported Bridge Design and Building

Various technologies and disciplinary tools were used and played an important role in supporting the bridge design and building processes in the project according to the video recording of the curriculum implementation. The project's technologies included smartboards, Google Classroom, and bridge building simulation programs. In order to create an authentic engineering design experience for students, multiple disciplinary tools, such as a shake table that simulated earthquakes and tested the strength of the bridges, were employed. Table 2 lists all the technologies and disciplinary tools that were provided/selected by the research team as well as the facilitators of the curriculum implementation that were used throughout the project.

Table 2. Technologies and Disciplinary Tools Identified

Type	Item
Technologies	Smartboard, Videos, Chromebooks, Bridge Builder Simulation Game*, Google Classroom, Eduweb's Bridge Type Earthquake Simulator**
Disciplinary Tools or Devices	Cardboard, Sponges, Ropes, Strings, Shake Tables, K'NEX Building Kits, 2-kg Weights, Decks

Note: *****Bridge Builder Simulation Game is a simulation game in which the students can select "lines" and "cables" within a budget to build bridges. **Eduweb's Bridge Type Earthquake Simulator is an online simulation program where students can simulate the whole process of bridge design, (i.e., choose bridge types, add safety features [e.g., bearings, shock absorbers] and test the strength of the bridge).

Based on the video recordings, the eight-week curriculum implementation could be divided into two parts. The first four weeks focused on developing necessary background knowledge (e.g., how earthquakes were formed, and quake-strength was measured) for problem solving through research and inquiry (e.g., what factors should be considered when designing a bridge). The last four weeks focused on the engineering design activities in which the students used disciplinary tools (such as the shake table) to aid the engineering design process. Table 3 presents the technologies and disciplinary tools that were used along with the context of use as well as the associated outcomes in the first four weeks, whereas Table 3 maps the technologies and disciplinary tools with each of the steps in the engineering design process presented in Figure 1.

Table 3. The Use of Technologies and Tools/Devices in the First Four Weeks

Technology/ Tools	Context	Learning Outcomes
Smartboard	The teachers presented inquiry questions (e.g., what should be considered when designing a bridge) regarding the activities the students would be working on to lead them through the thinking process.	The students learned the four different types of bridges and had some basic ideas of bridge design considerations.
Cardboard	A cardboard strip was used to create a curve and then students pressed down on the center to see what happened. The teacher then suggested adding an abutment at each end of the arch to make it stronger.	Students learned about arch bridge design and what an "abutment" was.
Sponges	Sponges with some top and bottom notches were used to simulate beam bridges. The sponges were put on a stack of books to create a beam bridge and the students were asked to observe how the top notch compressed and how the bottom notch spread out under tension.	Students learned about beam bridges, and what "compression" and "tension" were.
Ropes	Ropes were used to simulate the design of a cable bridge. Ropes were placed over students' heads and tied to their elbows and wrists to simulate a cable bridge. The ropes transferred the load of the bridge to the tower (i.e., their heads).	Students learned about cable bridges, and how the ropes in cable bridges transfer the load of the bridge to the tower.
Strings	The students were assigned into four different groups with materials to simulate the design of the four different types of bridges. Strings in this group were used to simulate the design of suspension bridges.	Students learned about suspension bridges, and how anchors support and make suspension bridges stronger and more stable.
Videos	Different videos were played during the implementation. For instance, a video was about the Golden Gate Bridge in terms of its costs, purposes, and history, etc. The teacher asked students various questions (e.g., the purpose of the bridge) to stimulate their thinking.	Students learned basic facts about the Golden Gate Bridge.
Bridge builder simulator	After the introduction by the teacher, the students were assigned to work on their own Chromebook and explored how to use the bridge building simulator. The students could select "lines" and "cables" within a budget to design a bridge so that a truck could successfully cross their bridge.	The students made different designs and learned what factors to consider when designing a bridge in a visual manner.
Notebook	The students were asked to draw their designs on the notebooks after watching the video of how engineers design bridges.	The drawing process required students to use what they had learned and applied that knowledge to design a bridge.
K'NEX building kit	After the students finished sketching their designs, they were assigned pieces of K'NEX rods and connectors and asked to design any bridge they wanted based on the information that they learned.	The students could turn their ideas into real objects by using the given K'NEX pieces.

As seen in Table 3, technologies like smart boards, videos, and the bridge building simulation program, served different purposes in supporting student learning. The smart board was used by teachers to present background domain knowledge about bridge building and to demonstrate the use of the simulation programs. In almost every session during the first four weeks of the implementations, multiple videos were played to visually explain engineering design ideas and concepts which are typically complicated for young/novice learners. For example, a video about the Golden Gate Bridge presented declarative knowledge about its history, purpose, and costs. The video was played as a generative strategy to engage students in thinking about what it takes to build a bridge, and helped foster students' interest in designing one.

Table 4. The Use of Technologies and Tools/Devices in the Last Four Weeks

Technology/Tools	Engineering Design Process Components	Context
White board	Identify the problem	The teacher guided the students to identify the problem that should be solved and wrote it down on the board: designing a bridge that is strong enough to withstand an earthquake.
White board	Research the problem	The teacher led the students to think about what should be considered to build an earthquake-resistant bridge, and wrote down factors, such as weight-bearing ability (2kg), stability (withstand a shake table for 15 seconds), type of design (e.g., arch, beam, cable, and suspension), and the length of its deck (at least 2 feet long), etc.
White board	Develop possible solutions and Select best possible solutions	What kind of bridges do we want to design? The teacher guided the students to eliminate the designs not suitable for the competition. They thought that the cable bridge (like the Golden Gate Bridge) was too delicate, therefore, they would not design a cable bridge. After the analysis, they decided to build a beam bridge.
Smart board	Develop possible solutions and Select best possible solutions	To strengthen students' understanding of how to choose the best design, the teacher presented different types of bridges with varying characteristics on a smartboard. The students discussed the advantages and disadvantages of each design and eliminated designs that were either too complex or too simple. They reached consensus on a design with intermediate structural complexity (a beam bridge). This design had more triangles in it, knowing that triangles are a more stable shape compared to other shapes like rectangles.
A model bridge designed with K'NEX	Select best possible solution	The teacher showed students a model bridge designed with K'NEX and identified the components (i.e., strong, stable parts) that they wanted to reconstruct and use in their own designs.
Piece of paper	Build prototype	After deciding on the bridge type, the students sketched their designs out on paper.
K'NEX building kit	Build prototype	Students started building a prototype following their design, including target components from the bridge model. During construction, the students discussed how to build and assemble small pieces together incorporating functional and structural considerations.
Smart board	Build prototype	The design they chose had only two beams, the teacher and students added another beam to the design. The students believed that by adding the extra beam, the force loaded on the deck could be distributed more evenly.
Deck and a 2-kg weight	Test and evaluate prototype	After the initial design was completed, the students put a 2-kg weight on the deck and slid it across the bridge to test whether it would sag or bend.
Shake table	Test and evaluate prototype and Redesign as needed	The students put the prototype bridge on a shake table and shook it for 15 seconds to test the strength of the bridge. It turned out that the bridge was strong enough to resist the shaking, but since the bridge was two times wider than the deck, the teacher suggested that the students should remove the extra beam to make it cost efficient per the evaluation criteria.
K'NEX building kit	Test and evaluate prototype and Redesign as needed	When students tried to put the deck on the beam bridge, the teacher asked them to think about making minor adjustments to the design so that the deck could be securely connected to the bridge. The students then tested out various ways to better support the deck and settled on a solution.
Shake table and K'NEX building kit	Test and evaluate prototype and Redesign as needed	The students put their revised bridge on the shake table and shook it for 15 seconds. They discovered that the footing of the design could be improved. A student proposed a different footing method and the group tried out the new design on the shake table. The new design was too complex and could not withstand 15 seconds of shaking. The group noted that the new footing design would cost more but did not yield more stability. They settled on a different footing design which was more cost-efficient and stable. The whole group collaborated and analyzed various bridge design factors regarding its stability, cost, and strength.

In the two bridge building simulation programs, the students were able to not only design and "build" a bridge, but also simulate the strength of the design. The simulations helped students understand what factors (such as load, tension, compression) to consider in order to construct a bridge successfully. In addition to the various technologies employed, some disciplinary tools (e.g., cardboard) were integrated as well. To further deepen students' understanding of different bridge types, the students were assigned into four groups with different construction materials (or disciplinary tools) to simulate each bridge type. For example, one group used cardboard to simulate an arch bridge, whereas another group used strings to learn and experience how force works on a suspension bridge. In the arch bridge group, students first bent cardboard strips to create a curve, and then pressed down on the center to see the effect of the force on both the shape and material. In the other groups, sponges were used to simulate beam bridges, and ropes for cable bridges. By experimenting with different materials, students were able to make connections between different bridge designs and the function of the forces, as well as how to make the bridges stronger and/or more stable by adding support structures (e.g., abutments for an arch bridge). Based on knowledge gained from the weekly sessions, students drew sketches of potential bridge designs in their notebooks and when ready, they were assigned pieces of K'NEX rods and connectors which they then used to prototype and build a bridge. To summarize, the different technologies and disciplinary tools had different purposes (i.e., knowledge development vs. application) and were implemented at different times. Table 4 lists the technologies and disciplinary tools used along with their purpose and context of use, as mapped onto each step of the engineering design process in Figure 1.

The purposeful alignment and integration of technology into specific stages of learning (i.e., from declarative knowledge to application) was taken a step further by mapping it to the engineering design process, making the experience more robust and interdisciplinary for students. For instance, the teacher guided the students to identify the problem needing to be solved, which could be mapped onto the first step (identify the problem) in the engineering design process. Figure 2 shows a picture of the above scenario of a teacher-guided problem-solving process.

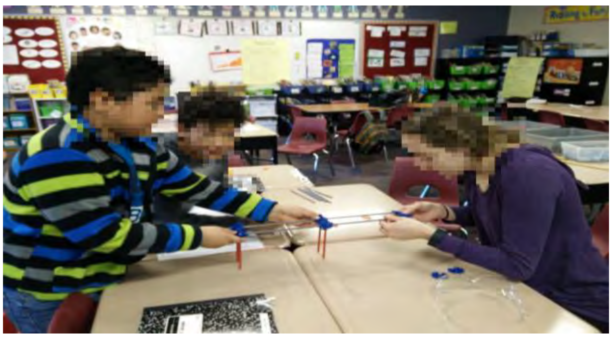

Figure 2. Teacher-guided Problem Solving

In terms of the building of an earthquake-resistant bridge, the teacher directed the students to think about the factors that should be considered according to the evaluation criteria for the final student design product (the bridge) in the final competition. The white board (a visualization tool) was also used to help students "develop possible solutions" and "select best possible solutions" when they discussed what bridge to ultimately design and build. To assist in determining what a "good" bridge design was, a model bridge constructed with K'NEX pieces was shown to students. From this, students then identified components and replicated the bridge in their own designs as depicted in Figure 3.

Figure 3. Student-Made Bridges using the K'NEX Kit

The data analysis connected to the fourth step in the engineering design process is "select best possible solutions". After this step, students began "building prototypes" in an effort to reconstruct a good design based on the predetermined evaluation criteria. Other tools like a deck, a 2-kg weight, and a shake table were employed to help complete the last several steps (test and evaluate prototype) in the engineering design process. The students placed their bridges on the shake table for 15 seconds to see whether the bridge could withstand the forces and would not break. The simulation gave students a glimpse into how professional engineers conduct testing their work. It is notable, however, that the use of a shake table as an earthquake simulation tool is hardly seen in existing literature despite it being both an effective technology and disciplinary tool to assist learning.

Over the course of the project, it appeared that the technologies and disciplinary tools were purposefully aligned and integrated into the curriculum to foster student learning and design activities. The purposeful alignment between technology use and learning activities guided students through the bridge design and building process from beginning to end, creating an engaging learning experience as shown in Figure 4.

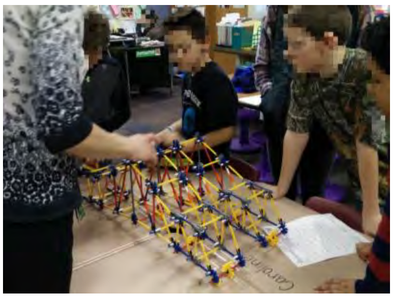

Figure 4. Engaging Bride-design and Building Experience

Engaging Technology in the Engineering Design Process

Based on the focus group interview, overall the students expressed enjoying their participation in the bridge design project using various technologies, and their perceptions are presented in Table 5. When asked about whether they wanted to see more projects like this in afterschool programs or in their regular classrooms, they unanimously answered “yes” without hesitation. For example, a student said:

What I like about it is that you are building something, and it is not something that you build [just] for fun, you do it for the competition [bridge design challenge].

When asked about whether they liked the kind of technologies used in the project, a student said:

I just like building bridges with K’NEX. And I like watching the videos [about building a strong bridge and damage caused by earthquakes].

Students were particularly animated by using Google Slides for making (creating and presenting) presentations together.

The interview questions also included why the students participated in the project, their perceptions of it, and why they thought the project was fun. The students’ responses revealed that it was due to the use of K’NEX, which made the bridge design and building challenge fun. For example, one student expressed that:

I just like playing with the K’NEX like whenever I get the K’NEX, I just start playing around with the pieces, see what I can build and experiment. I like the bridge building because we got [to] experiment. Experimenting is always fun, experimenting what will happen if you hit something with a hammer. Experimenting is fun.

Table 5.Students’ Perceptions of the Use of Technologies and Tools in the Project

Technology/Tools	Purpose	Sample Quotes
K’NEX building kit	Build bridge (engineering design)	I just like playing with the K’NEX like whenever I get the K’NEX, I just start playing around with the pieces, see what you can build and experiment. I like the bridge building because we got experiment. Experimenting is always fun, experimenting what will happen if you hit something with a hammer. Experimenting is fun.
		I like also building but I am sort of getting addicted to destroying something. In this bridge project, you sort of have to think more because you have to think what design would withstand shaking and it also has to withstand weights. So, it has to be able to hold enough weight even after the shaking.
		What I like about it is that you are building something, and it is not something that you build for fun, you do it for the competition.
Chromebook and Internet	Scientific inquiry	Yes, we need to use the internet to do research.
Video	Scientific inquiry	I like the video on the Golden Gate Bridge.
		I just like building bridges with K’NEX. And I like watching the videos.

Discussion and Conclusion

This study explored how technologies were used in an eight-week bridge building challenge to support students engineering design and problem solving, and how those students perceived the usage of technology in the project in terms of engagement and motivation. Moreover, it showcased the realization of a technology-supported curriculum and its expected outcomes, and the level of detail required when aligning technology with learning activities. When it came to the bridge design activities, different technologies and tools were employed to support students in accomplishing the design challenge. The study provides an example for instructors who have not used any technology in their classrooms on how to use various technologies to engage and motivate students in hands-on engineering design tasks. The use of technologies corresponded with various research and design activities during the design challenge, which also showed how technologies and tools were used to support the bridge design and building process. For example, the shake table, as a device combined with K'NEX building kit, enabled the students to build bridges and test the bridges' strength. The employment of a shake table also provided students with opportunities to experience what engineers would do in similar bridge design scenarios. In this study, the use of technology also focuses on research and scientific analysis to help enhance students' critical thinking skills (Thiry et al., 2011) and provide opportunities to practice thinking and working like scientists (e.g., the use of a shake table) (Seymour et al., 2004). With regard to students' perceptions of technologies and tools used in the project, the focus group interviews revealed that they had positive and enjoyable experiences in using technologies (e.g., K'NEX kits and videos) in not only researching various bridges but also designing and building the bridges.

While technology-supported learning is not new, there is a dearth of literature that investigates the use of technology, especially disciplinary tools (e.g., the shake table) for supporting engineering design activities. Many teachers assume that students who have grown up using computer technology in their daily lives have an aptitude to easily use any technology. However, technology competency continues to be a challenge for students, particularly those from low-income communities (Yang & Chittoori, 2022). The purposeful integration of technology in the learning process and the facilitation of teachers play a key role in how technology amplifies learning and supports student engineering design activities and problem solving. Thus, the focus should not be on the technology being used but on the learning outcomes that are supported by it. Technology should enhance and support student learning, not be a goal itself. Implications of this rather simple statement, however, are not necessarily simple. For example, Koehler and Mishra's (2009) TPACK framework illustrates the diverse types of knowledge that are necessary for working in modern, technology-rich learning environments when compared to traditional subject matter and pedagogical knowledge alone. Engineering design within STEM similarly requires additional knowledge and training by means of professional development for teachers, and collaboration among teachers/experts, to realize a technology-supported curriculum. Further, technology-supported learning environments should be made as authentic as possible to transform common learning settings into ones that can bring a discipline to life, such as the students' use of a shake table to measure the strength of the bridge they designed for their earthquake-prone community.

The transformative learning aspect is even more pressing when considering the inseparable relationship between how the various tools were developed, and the environment in which they were subsequently used in (Anthony, 2012; Engstrom, 2000; Koehler & Mishra, 2009; Luppicini, 2005). Moreover, many technology adoption efforts in schools and classrooms can be unsuccessful for numerous reasons such as resistance to change, lack of technical support, or intrinsic teacher beliefs (Kopcha, 2012; Palak & Walls, 2009). We live in a society that is ever changing, and the technology society uses is no exception. Technology plays a very important function in everyday life from augmenting traditional or familiar experiences (e.g., commerce to e-commerce) to complete transformation (e.g., mobile computing). Teaching must be an adaptive profession that evolves and transforms as well. Educators should embrace teaching methodologies that move schools nearer to where the students are using technology to harness their full potential, developing the problem-solving skills needed to confront the challenges they will face in the future. Thus, more studies regarding technology use as disciplinary tools to support students in scientific practices as professionals are needed. Specifically, there are few studies in which the technologies are used as disciplinary tools to simulate what scientists do in real world situations. Instead, these technologies are used to simply support students' learning of scientific inquiry and engineering design. Future research that aims to evaluate how various tools can better support problem-solving activities for the purpose of developing such tools is needed.

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