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Using Project-Based Learning Method As a Way to Engage Students in STEM Education

Mi Yeon Lee (Professor)[1*], Rolando Robles (Graduate Student)[2]
[1] Arizona State University, mlee115@asu.edu
[2] Arizona State University, rrobles9@asu.edu

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Science, Technology, Engineering, and Mathematics (STEM) education has been at the forefront of K-12 curricula in the technology-rich 21st century, with emphasis on how these fields reinforce each other in preparing students for a dynamic future. However, there is a need for greater attention to STEM education research in the mathematics education community, in particular to pedagogical approaches that facilitate integrating the mathematics component of STEM education. Toward this end, the authors report the outcomes of a Project-based Learning (PBL) unit in which upper elementary students integrated STEM elements by researching, crafting, testing, and evaluating kites they created by applying scientific knowledge of aerodynamics and mathematical knowledge of polygons, surface area, graphs, and data analysis. This unit, which the authors developed, implemented, and assessed, demonstrates how STEM subjects and in particular mathematics can be effectively integrated in upper elementary school classrooms through PBL.

Keywords: Project-based Learning, STEM education
ZDM classification: D43
2000 Mathematics Subject Classification: 97C90

I. INTRODUCTION

According to Margot and Kettler (2019), teachers value Science, Technology, Engineering, and Mathematics (STEM) education but report obstacles such as pedagogical challenges, curriculum challenges, concerns about students, concerns about assessments, and lack of teacher support. Thus, there is a need for STEM research that attends to the critical roles of teachers as designers and implementers of STEM curricula. In particular, there has been limited attention to STEM education research within the

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[*] Corresponding author: mlee115@asu.edu

mathematics education community (English, 2016). Math educators have therefore called for extensive investigation into the central role of mathematics in STEM education and its relationship to the other STEM disciplines (Anderson & Li, 2017) as well as pedagogical approaches and learning experiences that foster students' curiosity and active engagement in their own meaningful investigations.

Project-based learning (PBL), which by its nature calls for the integration of interdisciplinary knowledge, has been identified as an effective pedagogical strategy for helping students develop deep understanding of how scientific knowledge is constructed and applied (Krajcik & Blumenfeld, 2006). As previously stated by Lee (2015), in PBL, "students … experience a scientific inquiry process by using their knowledge and skills in science, technology, engineering, and mathematics to solve realistic problems" (p.110). The purpose of this article is to shed light on the value of the PBL approach in STEM education by reporting the outcomes of a mathematics-focused unit in an upper elementary school classroom and further to provide insight into the roles of teachers as implementers of STEM education.

II. PBL AND STEM EDUCATION

Following previous researchers, we have defined project-based learning as an "instructional method that fosters the learning and development of 21st century competencies and skills through problem solving and the integration and application of knowledge in real-world settings (Merritt, Lee, Rillero, & Kinach, 2017, p. 1). Thus, in this study, PBL involved constructing STEM knowledge through a project that required solving a real problem relevant to the students' own lives and interests. In traditional classrooms, completing a substantive project is usually the culminating event of a unit or semester after students have been pushed through homework assignments, lectures, and readings. However, in project-based learning, students are pulled through the curriculum by a driving question or realistic problem that provides a need to know, which is met by the integration of lectures, readings, and student-led research and problem-solving (Markham, Larmer, & Ravitz, 2003). Although related, project-based learning can be distinguished from problem-based learning, with which it shares a basis in constructivist learning theory, in its wider scope, interdisciplinary nature, and grounding in real-world problems rather than problems targeting specific topics in a particular field or discipline (Larmer, 2014; Savery, 2006). For this reason, a project-based learning unit often takes longer (e.g., one to four weeks) than problem-based learning (e.g., one hour to one week).

Although regarded as a relatively recent innovation in education, PBL was initially implemented in the field of medical education in the 1970s at McMaster University

(Barrows, 1996). To cultivate their problem-solving abilities, medical school students were engaged in identifying symptoms, making diagnoses, and prescribing treatments by interacting with actual or simulated patients or using written case studies. Through this inquiry-based learning process, the students not only learned medical content but also developed the clinical reasoning that is vital to the day-to-day practice of a doctor (Barrows & Tamblyn, 1980). The success of this approach encouraged a wide range of other fields such as advertising, architecture, business administration, engineering, nursing, and physical therapy also to adopt the PBL approach to teach content and skills needed in their professional settings (Barrows, 1996).

Research in various academic disciplines has demonstrated the greater effectiveness of PBL in higher education compared to traditional lecture-based instruction in terms of long-term retention and skills development (Strobel & Barneveld, 2009). Also, in literature reviews of PBL in K-8 science and mathematics education, some researchers reported the effectiveness of the PBL approach for improving K-8 students' academic achievement, knowledge retention, conceptual development, and attitudes toward science education (Drake & Long, 2009; Karacalli & Korur, 2014; Leuchter, Saalbach, Hardy, 2014; Wong & Day, 2008). For example, Karacalli and Korur (2014) found that students in the PBL group demonstrated higher academic achievement and knowledge retention as well as positive attitudes toward learning electricity in their lives compared to the control group in a traditional classroom. Also, Siagian, Saragih, and Sinaga (2019) found that PBL-oriented learning materials improved mathematical problem solving and metacognitive ability. Moreover, other researchers found that the inclusive and collaborative nature of PBL methods was useful for creating equitable experiences for elementary school students from underrepresented backgrounds, who are often marginalized in classrooms in terms of power, access, identity, and achievement (Cross, Hudson, Adefope, Lee, Rapacki, & Perez, 2012; Krajcik & Blumenfeld, 2006). However, there are still relatively few studies addressing PBL approaches in mathematics education, especially at the primary to early secondary levels (ages 5-14).

As human society looks to science and technology in order to solve many environmental and social problems, the multidisciplinary integration of knowledge across STEM fields will be increasingly important (Roehrig, Moore, Wang, & Park, 2012). This trend suggests that today's students will need a much higher level of preparation in these fields to deal with their citizenship responsibilities and the economic and ecological challenges of tomorrow than students in earlier times. Therefore, it is crucial that in their schooling years they learn to actively construct new knowledge and collaboratively engage in open-ended and authentic problem-solving (National Academy of Science, National Academy of Engineering, and Institute of Medicine, 2005). Thus, STEM disciplines and their central role in school curricula have recently become a primary interest of all stakeholders in K-12 education (Lee, 2014; National Science Foundation, 1996; Sanders, 2009), not just for their content but also for their cognitive benefits. The core of all STEM subjects is an emphasis on inquiry processes and problem solving toward the goal of constructing new knowledge (Wang, Moore, Roehrig, & Park, 2011). That is, students are expected to conceptualize authentic problems in science, technology, engineering, and mathematics, make conjectures as to possible solutions, plan and carry out experiments to test their conjectures, and revise their original conjectures from their experiments, repeating the inquiry process until they find viable solutions to their problems. Thus, the PBL approach evolves naturally into the inquiry process (Lee, 2014), which we believe is the hallmark of the scientific method and integral to STEM education.

Researchers have identified several essential components of the inquiry-based PBL approach in science education. These include investigating the nature of problems, collaborating in small groups, conducting student-centered iterative inquiry processes, accessing, available resources (e.g., library, PBL booklet, experimental kit), using various technologies (e.g., Internet, recording devices, software etc.), forming partnerships with the community, and communicating findings to an audience. Also important is the teacher’s role as a facilitator (Araz & Sungur, 2007; Karacalli & Korur, 2014; Leuchter, Saalbach, & Hardy, 2014; Wong & Day, 2008). Among these, investigating the nature of problems, a combination of individual and small group work, and student-centered iterative inquiry have been identified as core processes of the approach (Akmoglu & Tandogan, 2007; Drake & Long, 2009; Merritt et al., 2017). Similarly, Krajcik and Blumenfeld (2006) identified five definitive characteristics of the PBL approach: (1) the project or unit starts with a driving question that addresses an authentic problem; (2) students explore the driving question through problem solving that involves learning and applying important ideas of the discipline in an inquiry process; (3) students collaborate with other students, teachers, and community members to devise solutions to the target problem; (4) students use cognitive-support tools such as technology to aid their learning in the process of completing the project; and (5) students create final products related to the driving question and present them to their class and community members. This overall process is explicated below.

Once they have been given the driving question or target problem, often presented by a community member for whom the problem is a reality, students begin the problem-solving process by determining what they know or do not know about the problem and what additional information they need. When students have worked collaboratively to assemble the needed information, they brainstorm ways to construct a solution and negotiate agreement on the best approach, after which they plan and carry out their strategies along with their rationale for the solution they have produced. Finally, they jointly present their solution and reasoning to their audiences, from whom they receive feedback. In the course of this journey, students naturally engage in an authentic inquiry process with real outcomes using the knowledge and skills from science, technology, engineering, and mathematics they develop or gain during the process (Lee, 2014). In this way, they emulate the real work of professionals in STEM fields.

III. DEEPER EXPLORATION OF KEY ELEMENTS OF PBL: BUILDING LONG-FLYING KITES

1. PARTICIPANTS AND CONTEXT

Twenty-five sixth-grade students were involved in this study. The PBL unit, which was carried out in five 90-minute class periods, began with posing the driving questions; continued with small-group collaborations on designing, making, and testing kites, and culminated with sharing final reports and discussion of important ideas related to aerodynamics. The extended class periods allowed students time to explore their projects.

2. DATA COLLECTION AND DATA ANALYSIS

To investigate effectiveness of the PBL unit in STEM education, pre- and post-unit knowledge tests were administered. These two tests were not the same but comparable alternates Also follow-up interviews were conducted with all the participants after they had experienced the PBL unit. The pre-and post-tests included items about aerodynamics (or principle of lifting), the concept of a polygon, drawing polygons, using decomposing strategies for finding areas of polygons, finding areas of polygons in a coordinate plane, the concept of measures of center (mean, median, mode), and calculating measures of center. In follow-up interviews, we asked students to share their overall impression about the PBL unit and which components they enjoyed as well as to explain the inquiry-process with which they had engaged throughout the lesson.

To analyze the pre-and post-tests, we first created a rubric and scored the tests according to the rubric. Then we calculated means of the pre-test and the post-test using the Excel program in order to compare students' STEM-related knowledge and skills before and after the PBL unit. To analyze the interview data, we applied open coding method techniques of a grounded theory (Glaser & Strauss, 1967). We first provisionally assigned meaningful short-form labels to chunks of conversation initiated by a topic or interview question and then compared the resulting codes and merged them into new categories.

3. IMPLEMENTATION OF PBL UNIT

In this section, we describe the PBL unit on kite aerodynamics we designed and implemented in a sixth grade classroom, in which we consolidated the key elements from prior studies into four main components: (1) receiving and discussing the driving question, (2) designing and carrying out a solution in groups, (3) using technology to evaluate the design and product, and (4) presenting the final product to the class.

1) Posing the Driving Questions

It is critical to start PBL with driving questions that motivate students to engage in inquiry processes (Krajcik & Blumenfeld, 2006; Markham, Larmer, & Ravitz, 2003). This step involves not just posing a question but creating a scenario in which the question makes sense as a problem worthy of being solved. One way to make the kite problem authentic to students would be to show them a video in which a real staff member from a kite-producing company asks for help with designing a cost-effective, long-flying kite that would attract buyers. However, if such a video is not available, a teacher can create a script and play the role of the company representative or ask someone else to do so. In this study, we used a narrative approach in which the teacher imagined Benjamin Franklin on a June afternoon in 1752, observing the immanence of a thunderstorm and having the idea of flying a kite to demonstrate the electrical nature of lightning. For this purpose, he needed a kite design that would fly high and long enough to attract lightning and yet was economical to manufacture in case he needed to make several for repeated trials. The students were then invited to transport themselves back in time as kite-makers in Benjamin Franklin’s city and given the following driving problem:

> *How can you, as kite designers, provide suggestions for designing a kite which can fly for long time with the least expense? As final products, provide two things: (1) a final report to show your inquiry process and how you created the kite, and (2) a model kite built according to your specifications.*

To address the driving question, students first individually sketched their kite designs and provided reasons for their design decisions. Then the teacher asked them to form groups of three or four based on their preferences of whom to work with. For solving this problem, they needed to explore scientific concepts of aerodynamics, engineering design principles, and technological resources for collecting and analyzing data, all of which required a range of mathematical skills. Although the science standards of some countries (e.g., the Next Generation Science Standards [NGSS] in the U.S) do not specify aerodynamics as a topic, there are aspects related to flight and its association with force and motion concepts that can easily be connected to it. For example, the NGSS strand of third to fifth grade standards for understanding force and motion includes learning the effects of unbalanced forces on an object and resulting changes in motion. Also, the NGSS strand covering the same level standards for understanding energy and force relationships includes learning that contact forces transfer energy so as to change the motions of objects when they collide, and the sixth to eighth grade standards involve understanding how each object exerts a force on the other and how these forces can transfer energy between the two objects when they interact (NAS, 2013). Thus, teachers can make connections to some of these broader ideas through aerodynamics. Also, basic engineering practices specified in the NGSS, such as defining the problem, designing solutions, and optimizing design (i.e., design, test, redesign), tie in nicely with this kite project, enabling students to engage in an authentic scientific inquiry process. This project also directly incorporates content covered in the Common Core State Standards for Mathematics (Common Core State Standards Initiative [CCSSI], 2010), such as relationships among measures of angles, how these relationships influence the length of sides in polygons, and how they jointly determine surface area (refer to Table 1).

Table 1. Common Core State Standards for Mathematics Related to Kite Problem

Labels	Content
CCSSM.4.MD.6	Measure angles in whole-number degrees using a protractor. Sketch angles of specified measures
CCSSM.5.G.3	Understand that attributes belonging to a category of two-dimensional figures also belong to all subcategories of that category
CCSSM.6.G.1	Find the area of right triangles, other triangles, special quadrilaterals, and polygons by composing into rectangles or decomposing into triangles and other shapes; apply these techniques in the context of solving real-world and mathematical problems
CCSSM.6.G.3	Draw a polygon in the coordinate plane given coordinates for the vertices; use coordinates to find the length of a side joining points with the same first coordinate or the same second coordinate. Apply these techniques in the context of solving real-world and mathematical problems
CCSSM.6.SP.3	Recognize that a measure of center for a numerical data set summarizes all of its values with a single number, while a meaasure of variation describes how its values vary with a single number

2) Designing the most effective kite while engaging in scientific processes as a group

To support students' thinking processes while they were making their designs, the teacher asked them to predict what aspects might influence how well a kite flies. Various factors could influence a kite’s flying ability, but in this study, most students focused on the kite’s shape. Based on this discussion, the students selected various types of polygons (e.g., triangle, trapezoid, parallelogram, rhombus, rectangle, square, pentagon, hexagon etc.) for the surface of their kites.

Then, working within their collaborative groups, all students individually created their own kites using paper, thin bamboo sticks, glue, and string (see Figure 1). In this lesson, the teacher gave all students the same type of paper and other materials, so they considered only surface area for cost-effectiveness of construction. However, teachers can also guide students to think about other aspects by allowing them to select their own materials, requiring understanding of their various properties. After creating the kites, students guessed how long their kites would keep flying and then tested their predictions by flying them. During the experiment, students in the same group kept a record of how long each kite actually flew.

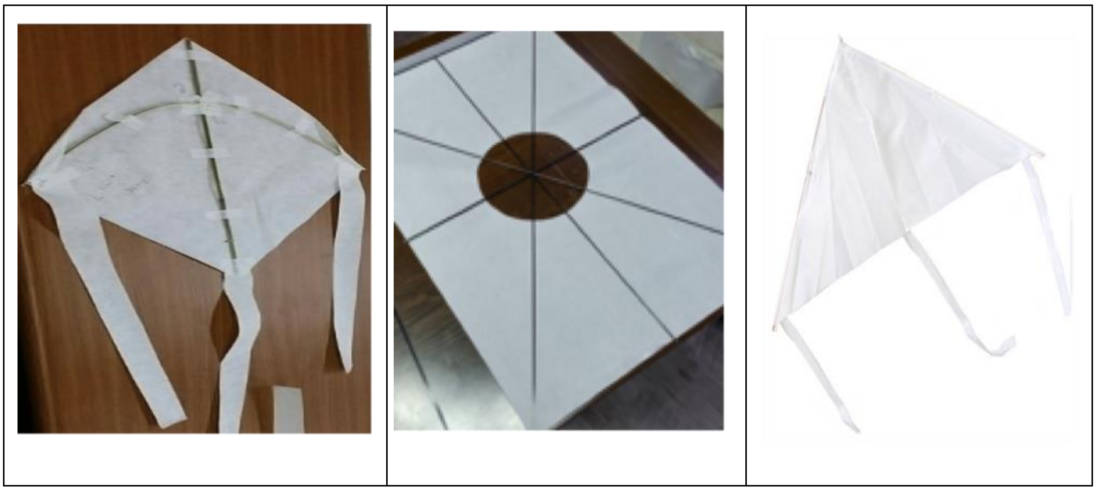
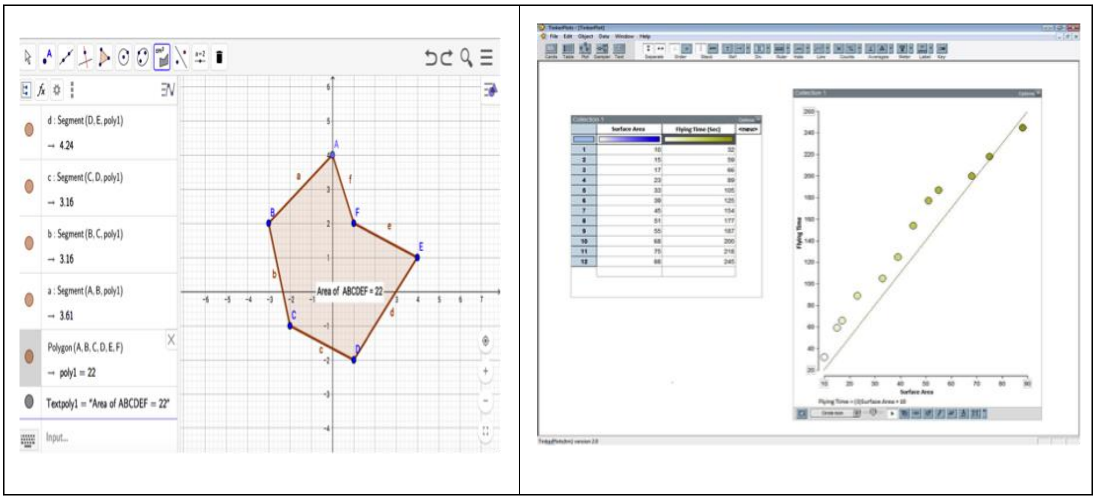


Figure 1. Examples of students’ kites

After the test, students within each group reflected on which kite flew the longest, why they thought it did, and what they would change if they were to design another kite. By comparing the relationship of the features of the kites to their flying time, students made conjectures on which factors might affect length of flying time. For this task, students considered various attributes of a kite such as the properties of the shapes based on angles, lengths of sides, and surface area. Using the information they generated, students in each group collaborated on a final kite design. The teacher encouraged students to keep a group journal while they were working on the project to prepare for their final presentation. The dual purpose of the small groups in this design is worth noting. They began as support groups in which each student designed and tested a kite individually and then functioned as teams that collaboratively produced a kite representing their collective knowledge and best ideas. This pattern ensured that each student participated in the full range of activities involved in the unit.

3) Using Technology to Evaluate the Effectiveness of a Kite

To gather further information needed for finding the best kite design, students could search the Internet or contact experts such as scientists in the area of aerodynamics. Also, in order to help them design their kites while gaining experience with thoughtful use of appropriate technology (Hudson, Cross, Lee, & Rapacki, 2012), they had access to two technology tools, Geogebra (http://www.geogebra.org) and TinkerPlots (Konold & Craig, 2005). Geogebra, an easy-to-use, free dynamic mathematics software program that allows students at all grade levels to bring together geometry, algebra, spreadsheets, graphing, and calculus, helped students sketch various 2D shapes and measure their dimensions on a coordinate plane (Figure 2 left). After using Geogebra to measure angles, lengths of sides, surface area, etc. on their kites, they used TinkerPlots, a dynamic statistical software package designed for fourth- through ninth-grade students that supports data organization, graphing, and finding measures of center (mean, mode, median), to make and test their conjectures about the most important factors affecting flying time. By clicking on and dragging icons to check the relationship between each factor and the kite's flying time, students could create tables and graphs for possible factors and find the most influential factor by comparing the distribution of the data or the slopes of the graphs (Figure 2 right).



d : Segment(D, E, poly1)
→ 4.24
c : Segment(C, D, poly1)
→ 3.16
b : Segment(B, C, poly1)
→ 3.16
a : Segment(A, B, poly1)
→ 3.61
Polygon(A, B, C, D, E, F)
→ poly1 = 22
Textpoly1 = "Area of ABCDEF = 22"

	Surface Area	Flying Time (Sec)
1	10	32
2	15	59
3	17	66
4	23	89
5	33	105
6	39	125
7	45	154
8	51	177
9	55	187
10	68	200
11	75	218
12	88	245

Figure 2. Examples of Geogebra to find the surface area of the kite (Left) and TinkerPlots to check the relationship between the surface area of the kite and the flying time (Right).

4) Presenting Final Products

To share their final products, students in each group prepared a final report and model of their final kite design and jointly presented their findings to the class and teachers. The purposes of this presentation were to give students opportunities to discuss solutions to the driving question and to receive feedback on their inquiry process and final kite designs. According to Markham et al., (2003), the effectiveness of PBL units should be evaluated on five criteria: (1) impact of performance (e.g., did creating a kite appropriately address the desired result posed in the driving question?), (2) work quality and craftsmanship (e.g., was students' final work organized and rigorous?), (3) adequacy of methods and behaviors (e.g., was their inquiry process thorough and their presentation clear?), (4) validity of content (e.g., did they base their analyses of kite-flying times and rationales for their kite designs on relevant factors such as angles, length of sides, or surface area and adequately support their choices?), and (5) sophistication of knowledge employed (e.g., did they display STEM knowledge that was complex and sensible for the task?). For effective reflection and peer-evaluation, the teacher provided a rubric including these criteria before the presentations.

IV. EFFECTIVENESS OF THE PBL UNIT IN STEM EDUCATION

To summarize, we designed a PBL unit with STEM contents and implemented it with 25 sixth-grade students in five 90-minute extended class periods. To measure the effects of the unit, we conducted follow-up interviews with the students. In the interviews, all students expressed their enthusiasm for the lesson. For example, some students pointed out their enjoyment of hands-on activity and group work with such comments as, "making my own kite and flying it with group members were so fun." Other students talked about the use of technology: "I like learning TinkerPlots and Geogebra. [The] two software programs were so cool." Also, 96% of students satisfactorily explained the inquiry process of the unit including understanding the driving question, making conjectures about the most effective kite features, designing their own kites, carrying out experimental testing, analyzing and comparing their results, and revising their original conjectures on the basis of evidence.

Moreover, to examine the effectiveness of the PBL unit, we administrated a knowledge test before and after the implementation of the unit. The average of pre-test was 68 points out of 100 points while that of post-test was 87 points. Also 92% of students demonstrated improvements in their scientific knowledge specifically related to aerodynamics (motions of kites) and mathematical knowledge related to finding surface area, drawing graphs, and data analysis.

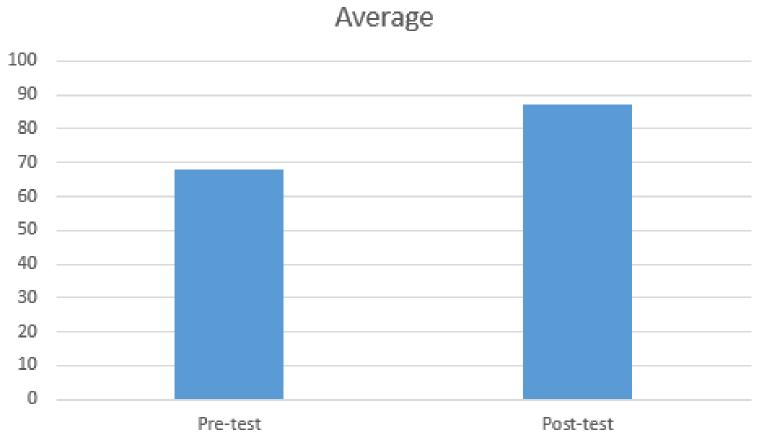


Figure 3. Students' academic gains after the PBL unit

In sum, students demonstrated that they learned about the scientific concept of aerodynamics; used the technological tools Geogebra and TinkerPlots to sketch the shapes of kites, measure their dimensions, and analyze the relationships among the measured data; applied engineering principles to designing and constructing their kites; and utilized mathematical knowledge of the features of polygons (e.g., angles, the length of sides), surface area, graphing, and data analysis throughout the project.

V. DISCUSSIONS AND CONCLUSIONS

The implementation of this PBL unit with upper elementary students demonstrated the seamless integration of relevant STEM elements throughout the inquiry process. At the beginning of the unit, students immediately connected with the challenge of creating a well-designed and long-flying kite that could be economically constructed, which motivated them to immerse themselves in the processes of inquiry, design, and construction to meet the challenge, followed by the satisfaction of making a substantive presentation that demonstrated their knowledge, creativity and skills. The results from the follow-up interviews and pre-and post-tests corroborated the effectiveness of the PBL approach in developing students' STEM knowledge. This finding aligns with Becker and Park's (2011) meta-analysis of studies investigating the effects of integrating STEM subjects on students' learning, which indicated that students who were engaged in integrative STEM subjects showed greater achievement than students studying subjects separately in large part because their rich learning contexts captured their interest and kept them engaged.

Students' interest in and positive attitudes toward STEM subjects could motivate them to pursue further STEM learning and future careers (Sanders, 2009). Becker and Park (2011) reported that early exposure to STEM fields promotes higher achievements in STEM subjects. Similarly, Sanders (2009) argued that "elementary grades offer unique opportunities for integrative approaches to STEM education and are absolutely the place to begin these integrative approaches" (p. 22). Also, because elementary school teachers remain with their students all day long and teach most subjects, they have more flexibility for curriculum adaption and scheduling for STEM integrative approaches (Zubrowski, 2002) than is possible with separation of subjects in later grades. However, numerous studies indicate that elementary teachers lack sufficient knowledge to integrate STEM subjects (Becker & Park, 2011) or have unclear perceptions of STEM integration (Wang et al., 2011).

In this regard, this study is meaningful in demonstrating how teachers can integrate STEM subjects through a PBL unit at the upper elementary level while addressing curriculum standards and teachers' roles as designers and executors of STEM learning experiences. Further implications may be drawn for extending the principle of integration to lower grades, using simpler projects and technology accessible to young learners, and upper grades, for example, by considering more than one factor on the outcome of a design. In this way, from the beginning, learners will be encouraged to be problem solvers, not just knowledge consumers, in school.

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