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What does Project-based Learning (PBL) Look like in the Mathematics Classroom?

Lorraine A. Jacques*

Eugene T. Moore College of Education, Clemson University, Clemson, SC, USA
*Corresponding author: lorraij@g.clemson.edu

Abstract This literature analysis addresses two issues concerning project-based learning (PBL) in the mathematics classroom: What it "looks like" and what its effectiveness in teaching skills. Articles addressing PBL in K-20 mathematics education were examined to determine what other discipline(s) the project included, what math topic(s) each addressed, and whether it demonstrated gains in students' mathematical skills. Results show that about half of the projects applied engineering with the mathematics. Gains in achievement were mixed and transferred to standardized or state assessments only when PBL was a core component of a school's curriculum. The lack of available research, however, discourages generalizations.

Keywords: *project-based learning (PBL), mathematics education*

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1. Introduction

Project-based learning (PBL) is experiencing a resurgence in American classrooms from early elementary school through college [1]. It allows students to learn content within a context, apply prior knowledge, and gain skills not found in traditional education, such as how to collaborate. PBL is a cornerstone pedagogy for STEM/STEAM approaches in the classroom as it allows the integration of several disciplines within one project [2]. And while there is growing research in the use and benefits of PBL in science classrooms, there is currently little research of PBL in the mathematics classroom at any grade level.

One reason for this lack of research may be the belief that formal mathematics should be taught before applications are introduced to the students. Nathan [3] reviewed several studies that investigated the beliefs surrounding the difficulty level of story problems and symbolic problems in arithmetic and algebra. Teachers consistently rated the symbolic problems as the easiest for students to understand and the story problems as the most difficult. When researchers in mathematics education were also asked to rate the difficulty level of these problems, the majority likewise said that the story problems would be the most difficult and the symbolic the easiest. Because of this belief, both groups felt that formal symbolic problems should be taught before students are introduced to applications in mathematics. Similarly, Rogers, Cross, Gresalfi, Trauth-Nare, and Buck [4] investigated teacher beliefs about what it means to be successful in their content area and how that influenced their implementation of PBL. Their case study included one mathematics teacher. He believed that success in mathematics was equivalent to success on standardized assessments. As he tried implementing PBL in his classes, he became convinced that students could not learn from projects unless they had first mastered procedural mathematics. This teacher left the study halfway through the school year because he did not see how PBL would help his students to master the formal mathematics that the state exam required.

The other reason PBL may not be studied as much in mathematics education is because teachers are not able to develop or implement a suitable project. For PBL to be effective, the project should engage students in exploration, be challenging, connect to the prior experiences of the students, and be of interest to the students [5]. Additionally, the teacher needs to be comfortable both in the non-mathematical content addressed in the project and in his/her abilities to be in a facilitator's role [6]. Finally, finding the time and resources to do a PBL unit is the most challenging barrier for teachers, as these projects take longer than traditional lessons to both develop and conduct [7].

This analysis of the literature will investigate two of the issues concerning PBL implementation in mathematics. First, what does PBL "look like" in the mathematics classroom? Second, can PBL increase students' skills in formal mathematics? Understanding the research in these two areas may help teachers and researchers to design PBL units easier and be more accepting of them as a valid approach to mathematics learning.

2. Method

In order to identify studies and articles addressing PBL in the mathematics classroom, this researcher used Thomas' [8] criteria for authentic PBL projects:

1) The students must be learning the central concepts through the project, rather than projects for enrichment and projects that applied prior learning.
2) The project centered on an ill-defined problem or driving question.
3) The project resulted in the construction of new knowledge for the students rather than a new way of considering already-learned material.
4) The project was student-driven with the teacher acting as a facilitator.
5) The project was realistic.

As an additional criterion, articles were included if they addressed mathematics learning for students in grades K-12 or undergraduates in college.

Academic Search Complete, ERIC, Educational Full Text and Google Scholar were searched using the following terms: project-based learning, PBL, mathematics, and constructivism. Although the search resulted in hundreds of articles, only thirty-one met the above criteria for PBL in mathematics education. Most of the rejected articles concerned science learning in STEM-based projects or pre-service teacher education. Seven of the accepted articles were authored by the same researcher, Brian Bottge. Of these seven, several addressed the same projects so the most recent article concerning each unique project was kept for this review. These included articles were also the most comprehensive studies that Bottge had conducted with each project. The final total number of articles kept for this review was twenty-seven.

The articles were then analyzed for the following information: grade level of the students, description of the project, mathematics addressed in the project, duration of the study, methodology, and results. The grade level of the students was then coded as follows: early elementary (K-2), late elementary (3-5), middle school (6-8), high school (9-12), and college. Two studies included students in grades five through eight; these were coded as middle school to represent the majority of the participants. The projects were then given a one-word descriptor indicating the primary discipline outside of mathematics that the project addressed:

- Engineering – Students built or designed a physical object.
- Technology – Students designed or developed computer software, such as a video game.
- Finance – Students worked with a budget.
- Agriculture – Students addressed agricultural issues.
- Science – Students worked in one of the core science disciplines, such as physics or biology.

Four articles described projects that addressed more than one of the above areas and were coded accordingly. Four articles did not describe a particular project but provided enough descriptions to suggest that the selection criteria were met and were thus coded as “unknown” if only one project was included in the article or as “various” if multiple courses/subjects were engaged in PBL.

3. Results

Examples of PBL was found in all grade bands, from early elementary to undergraduate classes, and addressed a multitude of topics in mathematics. The majority of the articles concerned high school students, with the next most prevalent representation being middle school students. Most of the articles described at least one project, three described schools with full PBL curriculums, and one described the project’s objectives rather than the project itself. Table 1 describes the number of projects for each grade level.

Two of the full PBL curriculum schools were high schools and one was a middle school. These were not included in the above counts.

The most popular discipline outside of mathematics addressed in these projects was engineering. A little more than half of the projects addressed engineering standards, as they had students building, designing, or analyzing a physical object. Engineering was also represented across all grade levels, although the majority of these projects were done by middle school students or older. Science and finance were equally the second most popular, with each being represented in seven projects. Science projects were primarily completed by high school and college students. Students in elementary or middle school were the only students who worked with projects involving finances. Table 2 shows the distribution of disciplines across grade levels.

A range of mathematics was addressed in the projects as well. Most of the projects addressed geometry and measurement topics. Working with functions and formulas, data and statistics, and fraction and ratio topics were the next most common mathematics addressed, although only data and statistics were included in the elementary grade projects. All but six of the projects addressed multiple math topics. Table 3 shows the distribution of math topics across grade levels.

Table 1. Number of projects per grade band

Grade Level	# Projects
Elementary – early	5
Elementary – late	4
Middle school	7
High school	9
College	5

Table 2. Number of projects per non-mathematics discipline

Discipline	# Projects	EE	LE	MS	HS	College
Agriculture	2	0	0	1	2	0
Engineering	14	2	1	5	4	3
Finance	7	2	1	4	0	0
Science	7	1	1	0	3	2
Technology	1	0	1	0	0	0
Various	3	0	0	1	2	0

EE=early elementary, LE = late elementary, MS = middle school, HS = high school; One agriculture project included both middle and high school students; one engineering project included both high school and college students; three projects addressed both engineering and finance.

Table 3. Number of projects per math topic

Math topic	# Projects	EE	LE	MS	HS	College
Geometry and measurement	13	3	2	6	2	0
Data and statistics	7	1	1	3	0	2
Fractions, ratios, proportions	6	0	0	4	2	0
Money	4	1	1	2	0	0
Charts and graphs	4	1	1	2	0	0
Functions and formulas	8	0	0	2	2	4
Trigonometry	3	0	0	0	2	1
Other	4	1	0	0	0	3

EE=early elementary, LE = late elementary, MS = middle school, HS = high school.

Table 4. Number of articles showing gains or no gains in student achievement

		# Articles demonstrating gains	# Articles not demonstrating gains
Math topic measured	Geometry	3	0
	Statistics	1	0
	Fractions	2	2
	Trigonometry	1	0
	Word Problems	0	1
State or standardized exam used		3	2
Students with LD measured		2	2
College grades		1	0
Total		13	7

To determine if PBL can help students increase their skills in formal mathematics, the findings reported in each article were analyzed to determine gains based on the math topic tested, if standardized or state exams were used, and if students with learning disabilities showed gains. Most of the studies that reported such findings only reported one or two of these measures, and fifteen of the articles did not measure student gains in mathematical skills. Table 4 summarizes the results of the remaining twelve articles. Although these are not enough studies to make generalizable remarks, it is notable that three studies failed to show gains in fractions and word problems skills. Similarly, PBL did not always translate to success on standardized or state exams and were not consistently beneficial for students with learning disabilities. However, the three articles that did report gains on state exams were also concerning schools that had integrated PBL throughout their mathematics curriculum rather than as a stand-alone project or intervention. An equal number of studies demonstrated and did not demonstrate gains for students with learning disabilities.

4. Discussion

What does PBL look like in the mathematics classroom? This review found that PBL primarily integrates engineering principals with the mathematics, regardless of grade level. Students build or design real objects and learn the mathematics through that process of building or designing. These projects primarily addressed geometry and measurement topics, which are natural and required skills when building, but also allowed students to work with data and fractions. Science was also a common second discipline for math PBL, especially with high school and college students. Those projects allowed students to learn math modeling and function analysis while addressing more advanced science topics like marine biology. However, some projects combined math and science in elementary grade projects. In these projects, students learned basic data analysis to understand the natural world around them. Also with younger students, finance was a common second discipline for math PBL, which is not surprising because understanding money is often taught in those grades.

Unfortunately, there is not enough evidence that PBL in mathematics actually helps students to increase their mathematical skills. Only twelve of the twenty-seven studies found for this review measured student achievement; the remainder measured attitudes towards mathematics or STEM careers, or did not research the students themselves. The studies that did measure achievement showed mixed results. While topic-specific assessments tended to show gains in achievement, state and standardized assessments did not unless the entire math curriculum at that school was oriented towards PBL. This suggests that PBL gains only transfer to standardized measures when it is a regular occurrence for students rather than an isolated event. Results for students with learning disabilities was also mixed, with an equal number of studies showing gains and not showing gains for these students. Further research may help clarify both of these issues.

Most troubling, however, is the lack of research available for PBL in the mathematics classroom. With only twelve studies measuring achievement, and reporting mixed results, we cannot say at this point in time if PBL is or is not an effective approach to math education. With only twenty-seven studies addressing PBL in mathematics at all, we cannot determine which disciplines pair well with mathematics in these projects. Nathan [3] found that teachers and researchers both believed that students would find story problems more difficult than symbolic ones. Perhaps this belief prevents researchers from looking closer at PBL for mathematics, since PBL is envisioned as being even more complex than story problems are. However, the studies in Nathan's [3] review also presented those story and symbolic problems to student and asked them to solve as many as they could. The students were more successful with the story problems.

References

[1] Burlbaw, L., Ortwein, M., & Williams, J. K. "The project method in historical context" In Morgan, J. R., Capraro, M. M., & Capraro, R. M. (Eds.). *STEM Project-based Learning: An Integrated Science, Technology, Engineering, and Mathematics (STEM) Approach*, Rotterdam: Sense Publishers, 2013, 7-14.

[2] Capraro, R. M. & Slough, S. "Why PBL? Why STEM? Why now? An introduction to STEM project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach" In Morgan, J. R., Capraro, M. M., & Capraro, R. M. (Eds.). *STEM Project-based Learning: An Integrated Science, Technology, Engineering, and Mathematics (STEM) Approach*, Rotterdam: Sense Publisher. 2013, 1-6.

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Articles Used in This Analysis

Arnold, A. The effects of project based learning on middle school students' attitudes and achievement in mathematics education (Doctoral dissertation), 2012.

Grade: MS
Project: Design and model a rollercoaster
Discipline: Engineering
Math: Geometry, basic statistics
Duration: 16 weeks

Bottge, B. A., Heinrichs, M., Mehta, Z. D., Rueda, E., Hung, Y., & Danneker, J. "Teaching mathematical problem solving to middle school students in math, technology education, and special education classrooms." *Research in Middle Level Education Online, 27*(1), 2004.

Grade: MS
Project: Building a variety of objects within a budget
Discipline: Engineering, finance
Math: Measurement, money, fractions
Duration: 7 months

Bottge, B., Heinrich, M., Chan, S., Mehta, Z., & Watson, E. (2003). Effects of video based and applied problems on the procedural math skills of average- and low-achieving adolescents. *Journal of Special Education Technology, 18*(2).

Grade: MS
Project: 2 video problems: buying pizza for a party, designing a pet cage; 1 group also applied learning by building a compost bin with the least amount of wood possible
Discipline: Engineering, finance
Math: Budgeting, scale drawings, unit conversions, mixed numbers
Duration: 22-30 classes

Bottge, B., Toland, M., Gassaway, L., Butler, M., Choo, S., Griffen, A., & Ma, X. "Impact of enhanced anchored instruction in inclusive math classrooms." *Exceptional Children, 81*(2), 2015.

Grade: MS
Project: Building a skateboard ramp, hover-board safety cage, and toy car stunt tracks; each within a budget
Discipline: Engineering, finance
Math: Ratios & proportions, fractions, measurement & geometry, graphing, statistics
Duration: 3+ months

Bunch, J., Robinson, J., Edwards, M., & Antonenko, P. "How a serious digital game affected students' animal science and mathematical competence in agricultural education." *Journal of Agricultural Education, 55*(3), 2013

Grade: HS
Project: Simulated environment where students cared for pigs
Discipline: Agriculture
Math: Numeracy including ratios, percents, fractions
Duration: 10 days

Cave, A. & Brown, C. "When learning is at stake: Exploration of the role of teacher training and professional development schools on elementary students' math achievement." *National Forum of Teacher Education Journal, 20*(3), 2010.

Grade: MS
Project: PBL charter school where the math curriculum uses 2 PBL-based programs
Discipline: Various
Math: K-8 math standards
Duration: multiple years

Filkcik, A., Bosch, K., Pederson, S., & Haugen, N. "The effects of project-based learning (PBL) approach on the achievement and efficacy of high school mathematics students: A longitudinal study investigating the effects of the PBL approach in mathematics education." *Proceedings of the National Conference on Undergraduate Research, 2012.*

Grade: HS
Project: PBL high school, various projects - only one described was bungee-jumping Barbie
Discipline: Various
Math: HS math standards
Duration: 5 years

Foutz, T., Navarro, M., Hill, R., Thompson, S., Miller, K., & Riddleberger, D. "Using the discipline of agricultural engineering to integrate math and science." *Journal of STEM Education, 12*(1&2), 2011.
Grade: MS & HS
Project: Operating a subdivision that integrates both suburban living and a farm; each grade level had a different focus of this problem
Discipline: Agriculture
Math: Multiple, especially function analysis and regressions
Duration: 5 years, not reported was how much of each year was used on this project

Goldstein, L., Burke, B., Getz, A., & Kennedy, P. "Ideas in practice: Collaborative problem-based learning in intermediate algebra." *Journal of Developmental Education, 35*(1), 2011.
Grade: college
Project: Determining if a gas additive improved fuel efficiency in cars
Discipline: Engineering
Math: Function analysis, systems of equations
Duration: 1 semester

Habash, R. & Suurtamm, C. "Engaging high school and engineering students: A multifaceted outreach program based on a mechatronics platform." *IEEE Transactions on Education, 53*(1), 2010.
Grade: HS & college
Project: Building robots with Lego Mindstorms (camp); student choice using mechatronics (undergrads) that get shared with high school classes
Discipline: Engineering
Math: Multiple - stated in article were fraction/ratio and function/relation concepts and some trigonometry
Duration: 1 week camp and integrated in the school year

Han, S., Caparo, R., & Caparo, M. "How science, technology, engineering, and mathematics (STEM) project-based learning (PBL) affects high, middle, and low achievers differently: The impact of student factors on achievement." *International Journal of Science and Mathematics Education, 13*, 2015.
Grade: HS
Project: Various
Discipline: Various
Math: Various
Duration: 3 yrs.; once every 6 weeks

Hansen-Powell, P. "Constructing knowledge." *Pia Connect Magazine (Synergy learning)*, *20*(3), 4, 2007.
Grade: EE
Project: Grade 1: observing bugs and nature; grade 2: marble track building; Grade 3: bridge building
Discipline: Science, engineering
Math: Data collection and analysis, geometry & measurement, estimation
Duration: Not reported

Kohler, B., Swank, R., Haefnew, J., & Powell, J. "Leading students to investigate diffusion as a model of brine shrimp movement." *Bulletin of Mathematical Biology, 72*, 2010.
Grade: college
Project: Investigating & predicting brine shrimp movement and population changes
Discipline: Science
Math: Math modeling, data analysis, statistics, differential equations
Duration: 5 class meetings

Lee, M. "Using weather to teach graphing." *Teaching Children Mathematics, 21*(4), 2014.
Grade: LE
Project: Charting weather and making predictions
Discipline: Science
Math: Bar and line graphs
Duration: 2 weeks

Lee, M. "Designing a children's recreation room." *Teaching Children Mathematics, 22*(2), 2015.
Grade: LE
Project: Design a recreation room with soundproofing, facilities kids like, and under $7000
Discipline: Finance
Math: Measurement, budgets, data analysis
Duration: 10 days

Lim, L., Tso, T., & Lin, F. "Assessing science students' attitudes to mathematics: A case study on a modelling project with mathematical software." *International Journal of Mathematical Education in Science and Technology, 40*(4), 2009.
Grade: college
Project: Modelling volcanic ash fall after an eruption
Discipline: Science
Math: Math modeling, function analysis, interpretation
Duration: Not reported

Meyer, D., Turner, J., & Spencer, C. "Challenge in a mathematics classroom: Students' motivation and strategies in project-based learning." *The Elementary School Journal, 97*(5), 1997.
Grade: LE
Project: Designing, testing, and evaluating kites
Discipline: Engineering
Math: Geometry
Duration: 1 unit, time not reported

Mohr-Schroeder, M. and 7 others. "Developing middle school students' interests in STEM via summer learning experiences: See Blue STEM Camp." *School Science and Mathematics, 114*(6), 2014.
Grade: MS
Project: Using LEGO robotics to design a green city, including powering wind turbines and designing a dam
Discipline: Engineering
Math: Measurement, using formulas, graphs, data analysis, informal ratios
Duration: 1 week

Ormsby, R., Daniel, R., & Ormsby, M. "Preparing for the future with games for learning: Using video games and simulations to engage students in science, technology, engineering, and math." *Astropolitics, 9*(2-3), 150-164, 2011.
Grade: LE
Project: Video game development
Discipline: Technology
Math: 3rd grade math standards
Duration: Full school year

Sabo, C., Burrows, A, & Childers, L. "Shaking up pre-calculus: Incorporating engineering into K-12 curricula." *Advances in Engineering Education, 4*(2), 2014.
Grade: HS

Project: Design, implement, and analyze ways to reduce vibration on buildings from earthquakes
Discipline: Engineering
Math: Trigonometry
Duration: 1 week

Sahin, A. & Top, N. "STEM students on the stage (SOS): Promoting student voice and choice in STEM education through an interdisciplinary, standards-focused, project based learning approach." *Journal of STEM Education, 16*(3), 2015.
Grade: HS
Project: Chapter projects where students present an experiment or activity to the class; individual year-long projects of their choice from a list of physics projects
Discipline: Science
Math: Varied
Duration: Chapter-long and year-long

Tran, N. & Nathan, M. "Pre-college engineering studies: An investigation of the relationship between pre-college engineering studies and student achievement in science and mathematics." *Journal of Engineering Education, 99*(2), 2010.
Grade: HS
Project: PLTW courses - Introduction to Engineering Design, Principals of Engineering, Digital Electronics
Discipline: Engineering
Math: Not specified
Duration: Each course lasted a full school year

Trinter, C., Moon, T., & Brighton, C. "Characteristics of students' mathematical promise when engaging with problem-based learning units in primary classrooms." *Journal of Advanced Academics, 26*(1), 2015.
Grade: EE
Project: Planning a party and purchasing items for an animal charity using donations received
Discipline: Finance
Math: Numeracy, geometry, charts and graphs
Duration: 1 month each

Tseng, K. H., Chang, C. C., Lou, S. J., & Chen, W. P. "Attitudes towards science, technology, engineering and mathematics (STEM) in a project-based learning (PjBL) environment." *International Journal of Technology and Design Education, 23*(1), 87-102, 2013.
Grade: college
Project: Created a multi-function electric vehicle for a contest
Discipline: Engineering
Math: Calculus, graph theory
Duration: 5 weeks

Tural, G., Yigit, N., & Alev, N. "Examining problems in project work executed in high schools according to student and teacher views." *Asia-Pacific Forum on Science Learning and Teaching, 10*(1), 2009.
Grade: HS
Project: Students came up with ideas
Discipline: Science
Math: Varied
Duration: Varied

Uyangor, S. "The effect of project-based learning on teaching of polygon and plane geometry unit." *The New Educational Review, 29*(3), 2012.
Grade: HS
Project: Only objectives described
Discipline: Unknown
Math: Polygons, similar triangles
Duration: 4 weeks

Zeid, A., Kamarthi, S., Duggan, C., & Chin, J. "Capsule: An innovative capstone-based pedagogical approach to engage high school students in STEM learning." *Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition*, 2011.
Grade: HS
Project: Teacher-designed projects that implement the engineering design process
Discipline: Engineering
Math: Various, geometry mentioned
Duration: Varied: 1 week – 1 school year