Full Paper: Where's the Math? A Case for Reconsidering Math in K-12 Engineering

Dr. Todd France, Ohio Northern University

Todd France helps coordinate the first-year engineering experience at Ohio Northern University, and directs ONU's Engineering Education program, which prepares students to teach engineering in grades 7-12.

Tena L. Roepke
Karli Katterle
Ms. Dua Chaker, University of Colorado Boulder

Dua Chaker is the Senior Project Engineer for the TeachEngineering Digital Library in the Integrated Teaching and Learning Program, College of Engineering and Applied Science at the University of Colorado Boulder.

Full Paper: Where's the Math? A Case for Reconsidering Math in K-12 Engineering

Introduction

"[We wanted them to] experience the fun side of engineering, and we weren't selling what all of engineering actually requires." – administrator about his high school's STEM curriculum [1]

It is indeed important for students to have "fun" in engineering, particularly those in lower grades who have yet to cross engineering off their potential career pathway list. Yet misrepresenting the significance of mathematics in K-12 engineering may give students a false sense of what engineering entails, arguably one reason that first-year college engineering students commonly cite math as a key area of struggle. Much like Wendy's classic "Where's the beef?" catchphrase in 1984 (which implored potential customers to reconsider the quantity of beef in other restaurants' burgers), educators might ask a similar question today about the quantity of math in K-12 engineering activities.

Initial discussions for this study began when faculty and undergraduates from Ohio Northern University's Math Education and Engineering Education programs collaborated on classroom activities intended to embed math content within hands-on engineering. Upon reflection of their own experiences, the research team (one math ed. faculty, one math ed. undergraduate, one engineering ed. faculty, and one engineering ed. undergraduate) recalled asking questions along the lines of "Where's the Math?" Anecdotally, the engineering design challenges in which they had participated and observed seemed to heavily emphasize visual and physical modeling (i.e., drawing and "building stuff"), but included minimal mathematical modeling. Thus, the team set out to systematically investigate if math is commonly used to inform decision-making in K-12 engineering activities, as would be expected of professional engineers. Such insight is useful for college engineering instructors, particularly those that teach first-year coursework, to better illustrate the authentic use of mathematics in their own curricula.

Relevant Literature

Plenty of literature suggests that engineering activities can provide a meaningful context for learning math [e.g., 2,3] – a practice that is recommended by the National Academy of Engineering [4] – and that engineering-based curricula can positively influence: a) students' STEM content knowledge, b) their appreciation of STEM fields' interconnectedness, and c) their attitudes towards STEM careers [5-13]. Interdisciplinary STEM approaches can also be leveraged to inform students about engineering, a field that is not widely understood by K-12 students [14]. While engineering curricula that clearly improve students' math comprehension do exist (such as earthquake vibration modeling in a pre-calculus class [10]), some studies suggest that engineering coursework has a propensity to improve students' performance in science much more than math [5,7,15].

What inhibits a streamlined union between K-12 math and engineering? One possible answer is the emphasis of mathematical practices over that of grade-specific math content, such is the case with many Project Lead The Way (PLTW) curricula [16,17]. (In one study of 140 8th through 10th graders, PLTW student gains in math were actually *less* than non-PLTW students [16].) Another possible culprit is the lack of STEM integration in Common Core *Standards for Mathematical Content* [18], which includes standards such as "Factor a quadratic expression to reveal the zeros of the function it defines" and "Construct an equilateral triangle, a square, and a regular hexagon inscribed in a circle" [19]. These discrete, grade-specific standards are inherently easier to assess and may appear more frequently in standardized tests, providing additional motivation for math teachers to avoid engineering curricula. Conversely, a sample of Common Core *Standards for Mathematical Practice (SMP)*, include "Reason abstractly and quantitatively," "Model with mathematics," and "Use appropriate tools strategically" – broadly defined goals that can prove challenging to assess accurately.

Assessment challenges notwithstanding, the ability to conceptualize, strategize, and reason, and possessing a positive disposition towards mathematics are critical to students' development in not only math, but all STEM fields and beyond [20]. Yet, according to Schoenfeld [21], many math curricula emphasize computations with "a set routine with no room for ingenuity" (e.g., memorizing steps to solve standardized test problems) at the expense of true understanding.

This penchant for focusing on discrete procedural steps is further confirmed in separate studies by Moye et al. [22,23]. While more than 90% of surveyed teachers supported active learning strategies (e.g., using manipulatives, working in groups through complex problems, and peer-teaching, all of which strongly align with SMPs), middle and high school math teachers reported the *lowest* levels of facilitating active learning environments (~37% and ~27%, respectively) of all subjects. These teachers instead often rely on traditional instructor-centered classrooms.

These data are particularly disappointing when considering missed opportunities to leverage active learning methods in math classrooms, as evidenced by a problem-based learning group that performed better than a traditionally-taught group in linear programming [24]. In the same vein, hands-on engineering activities can allow students to "discover" math concepts at a deeper level, as demonstrated in a pre-calculus course [10].

But are high-quality, interdisciplinary activities readily available? Perhaps not, as suggested by Katz and Klass-Tsirulnikov [25], who were unable to find interesting activities to introduce students to basic matrix algebra (then went on to design their own using an "artificial neural network for character recognition"). In a separate study of ten sample STEM high schools, researchers found that only four schools had implemented instruction connecting the STEM disciplines [26]. This lack of connectivity has been mirrored in the past by a National Academy of Engineering study, which concluded, "Existing curricula do not fully exploit the natural connections between engineering and the other three STEM subjects" and "…very few curricula or professional development initiatives reviewed by the committee used mathematics in ways that support modeling and analysis" [4].

Moreover, engineering activities that do include math often do so minimally and/or simplistically. In one study of high school students in an engineering class, 36% of their time was spent on math-related tasks, a significant time allotment (computer-aided design and sketching consumed the remaining time) [27]. Yet of this dedicated math time, 23% was categorized as "description" (quantifying dimensions and calculating costs), 9% as "function" (typically simplistic, such as calculating area), and just 4% as "explanation" (informing design decisions). In another study, no more than 3% of high school engineering students' time was spent on math-related activities in an open-ended design problem, where even individuals in higher-level math courses commonly opted for trial-and-error approaches [28].

Others have reported similar findings, with few high school engineering students using more than basic math representations or models in their designs [29], instead performing tasks such as taking measurements and presenting data [30]. Thus, it is particularly important for college engineering instructors to illustrate the importance of tasks such as solving for unknowns, modeling, and interpreting data to inform decision-making. Since a key aspect of mathematical proficiency is the ability to employ problem-solving strategies, and because students are influenced about the nature of math from classroom experiences, it stands to reason that, especially in an engineering setting, they should NOT be consistently experiencing math as a) having only one right answer, b) having only one correction solution pathway, c) a memorization process, d) a solitary activity, e) solvable in five minutes or less, or f) unrelated to the real world, as suggested by Schoenfeld [31].

Surface level integration of math and engineering (or none at all) can lead to misconceptions about the engineering profession, as explained by a high school teacher that divided her time between a traditional math classroom and a project-based engineering classroom: "…after like two minutes, they're like, 'What? This isn't math class.'" [1]. In her engineering classroom, she consistently encountered obstacles when presenting math content to her students. And yet, *these same students* would notably NOT "get really bored really easily and really distracted" when presented with math concepts…so long as they were in this teacher's math classroom!

Goals and Process

To carry out this investigation, the research team decided to evaluate a sample of engineering activities. Due to the availability of free, easily-searchable, standards-aligned materials, TeachEngineering (teachengineering.org) was selected as the study's source. This digital library is a popular resource for 1,800+ K-12 engineering lessons and activities, with most curricula created by professors, graduate students, and K-12 teachers associated with National Science Foundation-funded engineering colleges. Authors represent about 70 different institutions.

To narrow the study's scope, the research team filtered for hands-on activities using two criteria:

a) Time frame ≤ 2 hours (short-term activities were deemed more easily integrated into math classrooms, and thus likely more widely adopted)
b) Aligned with Common Core State Standards for Math (CCSSM) grades 7-12 (the grade band of the undergraduate researchers' licensure area)

Activities were then sorted in order of popularity. At the outset, all four members of the research team independently evaluated the first three activities, then collaborated to ensure key activity elements were being identified accurately. The elements that were recorded include:

- Discrete math tasks (e.g., one activity's tasks included: measure distance, calculate volume, create a scatter plot, and calculate force)
- If the math was primarily *design-oriented* (e.g., to optimize a dimension via open inquiry) or *procedural* in nature (e.g., following specific steps in a calculation)
- If the math occurred *before*, *during*, or *after* the activity's hands-on phase
- If the math was *required* to complete the activity, *helpful* to complete the activity, or simply *tangential* to the activity

- The total time of the activity (as reported by the authors) and the research team's estimated time required for the identified math tasks
- If the suggested CCSSM were aligned well with the activity, and any suggestions for other math standards that could be aligned

The research team then progressed as follows:

1. Undergraduate researchers independently reviewed each activity
2. Undergraduate researchers came to an agreement on each activity element above
3. The undergraduates presented their findings to one or both faculty (who had also independently reviewed each activity), all coming to an agreement on each element
4. The research team shared their findings with a TeachEngineering editor, who provided feedback and made some adjustments to the published activities

This systematic process was time intensive, consuming nearly 400 hours of student time alone, and yielded evaluations of 30 total activities – an admittedly small sample size of the more than 1,800 curricula on TeachEngineering. Yet, rather than taking a cursory approach by skimming through activities (thereby yielding a higher quantity of evaluations), the research team conscientiously decided to pore over each activity in detail, collaborate on findings, and compromise to estimate the math content in each.

Results

Of the 30 activities reviewed on Teach Engineering as part of this study, 11 included at least some open-ended design (preferred for SMPs), while 19 were largely procedural with singular correct answers. All but one of the activities included at least some basic math content, with each activity averaging about four discrete math tasks (e.g., draw vectors with stated direction and magnitude). Roughly one-third of the average activity time was estimated to be math-related (more than the research team initially anticipated) though this figure varied widely. For instance, less than 15% of the time was estimated to be math-related in nine activities.

Notably, only three activities included math tasks that occurred *before* the hands-on phase: two required students to use a budget to constrain their designs; one required students to complete a worksheet to gain experience with the Bernoulli equation before applying this equation later on. The remaining math tasks occurred *during* the hands-on phase (e.g., measuring) or *after* the hands-on phase (e.g., calculating averages, plotting data).

Considering the utility of the math tasks, just four activities were deemed to include math that was *tangential* to successful completion (which could be interpreted by students as "busy work") while six activities included math that was *helpful*, but not required, for successful completion (e.g., creating a data plot to illustrate a relationship, but not making any decisions based on the discovered trend). Thus, nearly two-thirds of the activities included math that was *required*, a commendable quantity. These math-embedded activities thereby aligned well with the "beads-and-threads" conceptual model presented by the National Academy of Engineering, whereby "threads" of math, science, technology, and design are integrated into manageable engineering projects (the "beads") [4]. Unfortunately, none of the reviewed activities included math that was used to inform decisions, make predictions, or confirm experimental data (i.e., modeling).

The research team also determined that 70% of the suggested CCSSM were aligned well with the published activities (14 activities had 100% alignment), with most misalignments easily corrected with minor modifications. Many other CCSSM were identified as potential additional standards that could easily be included in the reviewed activities. (Notably, a TeachEngineering editor (and co-author of this paper) was very receptive to suggested edits.) This suggests that educators familiar with relevant learning standards and related content can utilize freely-available activity plans by leveraging their expertise when adopting material (though many educators may be averse to this due to a lack of formal training in engineering education).

Discussion

While engineering is a natural fit for engaging students in math and science, actually doing so can be challenging. Consider the case of 48 middle school teachers that spent a year developing 20 engineering design challenges aligned with math and science standards – post-assessment of their work determined that, even with their best intentions, several activities simply did not include much math [32]. Or consider the 45 science teachers that participated in five summer workshops to better understand STEM integration; the units they developed were similarly short of mathematics [33]. In another study, students involved in a *months-long* "problem-solving to prototype" engineering project exhibited minimal positive change in their interests towards a math-related career, which can be inferred as a lack of math inclusion [34]. This literature agrees with the findings of this study – there is opportunity for not only increasing the amount of math content in engineering activities, but also for reshaping the type of math tasks included.

These shortcomings are likely partially attributable to a number of factors, including educators' lack expertise and confidence across all STEM disciplines [15], suggesting a need for curricular support and professional development [35]. This could include workshops to become more familiar with an engineering design process and opportunities to collaboratively develop activities with STEM colleagues. Such continuing education must emphasize the importance of explicitly making connections among the STEM disciplines in the classroom, since identifying these connections may not come naturally to students [15,36]. For example, in a study of more than 1,000 8th and 9th graders participating in an engineering design challenge, the experimental group was required to develop math equations with support of hands-on manipulatives; this group showed greater improvement in quantitative probability and math modeling [37]. The key caveat here is the *required* aspect of the intervention. That is, if students are able to complete an activity without using math, they won't, as suggested by Kelley et al. [28], who advise that activities need to engage students in the *analysis* and *optimization* stages of engineering. This differs from the math tasks that typically happen during or after the hands-on phase. Instead, Silk et al. recommend taking a more authentic and transferable approach by a) explicitly highlighting the connections between the math and engineering content, and b) including contexts that lead to generalizable solutions (e.g., programming a robot to travel any distance based on user inputs, not just a single given distance) [2].

It is worth noting that only five of the thirty evaluated activities were targeted towards high schoolers, while the remainder were targeted towards grades 7 and 8 (recall that activities were sorted by popularity). This can be partially explained by the greater amount of activities for junior high school (n = 500) than upper-level high school (n = 302 for grades 11-12). But there is likely something more significant at play here. Since many K-12 engineering curricula strive for inclusiveness, as well it should, the grade level of math often falls below the grade level of the activity (e.g., in this study, several activities targeted towards junior high included sixth-grade math standards). This asymmetric STEM integration may discourage high school engineering teachers from challenging strong students with upper-level math (e.g., if an 10^{th} grade teacher filters for 10^{th} grade activities and finds 8^{th} grade standards), which may thereby support engineering-math connection misconceptions. Moreover, math teachers may be reluctant to implement engineering activities that emphasize SMPs since these can be difficult to assess, and are perhaps less relevant in standardized tests that emphasize subject-specific content.

Yet the most significant finding from this study is the need for more activities that provide authentic opportunities for students to experience engineering with math on the front end. Classroom activities such as performing calculations to inform decisions *before* finalizing designs and predicting prototype performance data can offer students additional motivation and a more well-rounded understanding of the value of mathematics in engineering.

Acknowledgement
This study was supported by NSF's Robert Noyce Teacher Scholarship Program (#1758335).

References

[1] Student Achievement." 2015 ASEE Annual Conference.
[2] E. M. Silk, R. Higashi, R. Shoop, and C. D. Schunn (2010). "Designing Technology Activities to Teach Mathematics." The Technology Teacher, December/January, pp. 21-27.
[3] L. Katehi, G. Pearson, and M. Feder (2009). "The status and nature of K-12 engineering education in the U.S." The Bridge 39, 3, pp. 5-10.
[4] National Academy of Engineering, & National Research Council. (2009). Engineering in K-12 Education: Understanding the status and improving the prospects. Washington, DC: The National Academies Press.
[5] I. Zeid, J. Chin, C. Duggan, and S. Kamarthi (2014). "Engineering Based Learning: A Paradigm Shift for High School STEM Teaching." International Journal of Engineering Education 30(4), pp. 876-887.
[6] M. S. Zarske, J. L. Yowell, H. L. Ringer, J. F. Sullivan, and P. A. Quinones (2012). "The Skyline TEAMS Model: A Longitudinal Look at the Impacts of K-12 Engineering on Perception, Preparation, and Persistence." Advances in Engineering Education, pp. 1-26.
[7] K. Williams, I. Igel, R. Poveda, V. Kapila, and M. Iskander (2012). "Enriching K-12 Mathematics and Science Education Using LEGOs." Advances in Engineering Education, pp. 1-28.
[8] P. R. Hernandez, R. Bodin, J. W. Elliott, B. Ibrahim, K. E. Rambo-Hernandez, T. W. Chen, and M. A. de Miranda (2014). "Connecting the STEM Dots: Measuring the Effect of an Integrated Engineering Design Integration." International Journal of Technology and Design Education (24), pp. 107-120.
[9] E. McGrath, S. Lowes, P. Lin, and J. Sayres (2009). "Analysis of Middle- and High-School Students' Learning of Science, Math, and Engineering Concepts Through a LEGO Underwater Robotics Design Challenge." American Society for Engineering Education, pp. 1-16.
[10] C. Sabo, A. Burrows, and L. Childers (2014). "Shaking Up Pre-Calculus: Incorporating Engineering into K-12 Curriculum." Advances in Engineering Education, pp. 1-27.
[11] P. Cantrell, G. Pekcan, A. Itani, and N. Velasquez-Bryant. "The effects of engineering modules on student learning in middle school science classrooms." Journal of Engineering Education 95, no. 4 (2006): 301-309.
[12] P. Hylton (2010). "Using Motorsports Design Concepts to Further STEM Education." The Journal of Technology Studies, 36(1), pp. 1-5.
[13] J. B. Listman, and V. Kapila (2016). "Impact of Engineering Curricula and Student Programming on STEM Attitudes Among Middle School and High School Students." 123rd ASEE Annual Conference and Exposition, New Orleans, LA.
[14] J. Mitchell-Blackwood, M. Figueroa, C. Kokar, A. Fontecchio, and E. Fromm (2010). "Tracking Middle School Perceptions of Engineering during an Inquiry Based Engineering and Science Design Curriculum." American Society for Engineering Education, pp. 1-22.
[15] M. Nathan and G. Pearson (2014). "Integration in K-12 STEM Education: Status, Prospects, and An Agenda for Research." 121st ASEE Annual Conference and Exposition, Indianapolis, IN.
[16] N. A. Tran and M. J. Nathan (2010). "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, pp. 143-157.

[17] A. Prevost, M. Nathan, B. Stein, and A. Phelps (2010). "The Enacted Curriculum: A Video-Based Analysis." American Society for Engineering Education.
[18] M. M. Capraro and S. B. Nite (2014). "STEM Integration in Mathematics Standards." Middle Grades Research Journal, 9(3), pp. 1-10.
[19] National Council of Teachers of Mathematics. "Common Core State Standards for Mathematics."
[20] National Research Council. (2001). "Adding it Up: Helping Children Learn Mathematics." Washington, DC: National Academies Press.
[21] J. D. Bransford, A. Brown, and R. Cocking (2000). "How people learn: Mind, brain, experience and school," expanded edition. DC: National Academy Press, Washington.
[22] J. Moye, W. E. Dugger Jr., K. N. Starkweather (2016). "Learn Better by Doing Study - Third-Year Results." Technology and Engineering Teacher, (September), pp. 16-23.
[23] J. Moye, W. E. Dugger Jr., and K. N. Starkweather (2017) "Learn Better by Doing Study - Fourth-Year Results." Technology and Engineering Teacher, (November), pp. 1-8.
[24] S. B. Nakhanu and A. M. Musasia (2015). "Problem Based Learning Technique and its effect on Acquisition of Linear Programming Skills by Secondary School Students in Kenya." Journal of Education and Practice, 6(20), pp. 1-8.
[25] S. Katz and B. Klass-Tsirulnikov (2007). "Using Neural Networks to Motivate the Teaching of Matrix Algebra for K-12 and College Engineering Students." American Society for Electrical Engineering, pp. 1-15.
[26] S. A. Scott (2009). "A Comparative Case Study of the Characteristics of Science, Technology, Engineering, and Mathematics (STEM) Focused High Schools." George Mason University, Fairfax, VA.
[27] T. J. Huffman, N. Mentzer, and K. H. Becker (2013). "High School Student Modeling Behaviors During Engineering Design." 120th ASEE Annual Conference and Exposition, Atlanta, GA.
[28] T. Kelley, D. C. Brenner, and J. T. Pieper (2010). "PLTW and Epics-High: Curriculum Comparisons to Support Problem Solving in the Context of Engineering Design." Research in Engineering and Technology Education. National Center for Engineering and Technology Ed.
[29] N. Mentzer, T. Huffman, and H. Thayer (2014). "High School Student Modeling in the Engineering Design Process." International Journal of Technology and Design Education, 24, pp. 293-316.
[30] K. Welty, L. Katehi, and G. Pearson (2008). "Analysis of K-12 engineering education curricula in the United States - A preliminary report." American Society for Engineering Education Annual Conference and Exposition, Pittsburgh, PA.
[31] A. H. Schoenfeld (2007). "What is Mathematical Proficiency and How Can It Be Assessed?" In A. H. Schoenfeld (Ed.), Assessing Mathematical Proficiency (pp. 3-15). New York, NY: Cambridge University Press.
[32] S. S. Guzey, T. J. Moore, and M. Harwell. (2016). "Building Up STEM: An Analysis of Teacher-Developed Engineering Design-Based STEM Integration Curricular Materials." Journal of Pre-College Engineering Education Research 6(1), pp. 11-29.
[33] E. Ring-Whalen, E. Dare, G. Roehrig, P. Titu, and E. Crotty (2018). "From Conception to Curricula: The Role of Science, Technology, Engineering, and Mathematics in Integrated STEM Units." International Journal of Education in Mathematics, Science, and Technology, 6(4), pp. 343-362.
[34] S. H. Newton, M. Alemdar, R. A. Moore, and C. J. Cappelli (2018). "An Investigation of Students' Experiences in a K-12 Invention Program." 125th ASEE Annual Conference and Convention, Salt Lake City, UT.
[35] K. S. Holstein, and K. A. Keene (2013). "The Complexities and Challenges Associated with the Implementation of a STEM Curriculum." Teacher Education and Practice 26(4), pp. 616-636.
[36] C. G. Valtorta and L. K. Berland (2015). "Math, Science, and Engineering Integration in a High School Engineering Course." Journal of Pre-College Engineering Education Research, 5(1), pp.14-29.
[37] A. M. Schuchardt and C. D. Schunn (2015). "Modeling Scientific Processes with Mathematics Equations Enhances Student Qualitative Conceptual Understanding and Quantitative Problem Solving." Science Education (100), pp. 290-320.