What is the Role of Engineering in Secondary Education? A Case for Integrating Crosscutting Engineering Skills in K-12

Otsebele Nare and Jale Akyurtlu
Hampton University

Abstract

This paper explores the role that engineering educators can play in building engineering skills in K-12 level, as demonstrated in the Hampton Roads Partnership for Algebra (HR-PAL) project in Virginia. The premise of the project is that the engineering skills should be developed in mathematics and science classes. This paper focuses on the development of problem solving and algebraic thinking skills at K-12 level, using a basic engineering approach, namely 'system analysis', in solving word problems. The results of the project presented here indicate that the problem solving skills of in-service teachers of technology and mathematics, specifically algebra, may be enhanced/developed by a structured problem-solving program employing 'system analysis' in professional learning communities (PLC), such as teachers' circles and summer institutes. Thus, it was concluded that the application of 'system analysis' may be used as a model for integrating crosscutting engineering fundamental skill of problem solving and design across different subjects.

Keywords

K-12 Engineering Education, STEM education**.**

Introduction

The responsibility of engineers is to solve problems or develop solutions in response to human needs. Therefore, every person should be educated to understand the context of engineering thinking, because the way people live and interact is impacted by engineering and technology. In this same context, a number of models[1,2,3,4] for integrating engineering in K-12 have been developed as the Next Generation Science Standards require. The emphasis of these models is to ensure that all students are technologically literate and that there should be collaboration in educating future engineers. As a result of these models, there has been an emergence of K-12 engineering education standards as well. The problem with the rapid changes in engineering at K-12 has been precipitated by the shortage of qualified engineering teachers. In addressing this issue, Farmer et al[1] have developed Standards for Professional Development for K-12 Teachers of Engineering as a way to adequately prepare and support the educators who will teach engineering in K-12 classrooms. Standard C of professional development for teachers of engineering makes clear how engineering design and problem solving should offer a framework for teaching science, mathematics, language arts, reading, and other subjects. In the same vein, professional development programs for teachers in non-engineering subjects like mathematics, science, technology, etc., should offer a foundation for understanding engineering thinking.

According to data from the Business-Higher Education Forum[5], less than 20 percent of America's high school students are math-proficient and interested in pursuing careers in STEM.

In addition to this, close to 70% of high school students are not interested in STEM at all. Yet the demand for engineers and advanced technology professionals is expected to continue growing in the coming years. Engineering educators have a role in improving interest in STEM as well as proficiency in math as highlighted by the 2014-15 ASEE president's statement when he said, "Most recently, there has been much attention paid to the role of engineering in STEM education in our elementary and secondary schools. ASEE is assuming a leadership role in defining how engineering can be addressed in a meaningful yet age-appropriate way to motivate young people to learn science and mathematics, to inspire them to pursue engineering…"

The emergence of K-12 engineering education is precipitated by industry demands as well as the fundamental challenges that the students matriculating in engineering departments are confronted with, such as struggling with fundamental math skills as in secondary education algebra. As a result, some colleges are teaching fundamental engineering math courses for college freshmen whereas some pre-college institutions are integrating technology as a way of interactively addressing the fundamental gap[6,7]. In responding to the challenges especially in preparation of students for an engineering career path, it is common to hear the terms such as the need to increase rigor and content, improve conceptual understanding, add more hands-on learning activities, and assessment among others in reference to student learning; these are highlighted in new standards of learning. What is missing at times is the emphasis on giving teachers time for the training and professional development to effectively teach the subject matter. Continuous teacher training and professional development are required to adapt teachers to the new rigor in standards, deepening of content knowledge, and assessment requirements[8,9,10,11]. In light of these challenges, engineering has a role in secondary education, in student learning and in preparing teachers. This paper discusses the framework of a role engineering can play in teaching algebra at secondary education level with the approach that the most important skills that a student is expected to acquire in the algebra courses is problem-solving and algorithmic thinking.

Partnership for Algebra Framework

Moore et al[12] have presented a framework for quality K-12 engineering education that is in line with the recommendations of the 2009 National Research Council report on K-12 Engineering Education[13]. The report made recommendations that K-12 engineering education should focus on (i) emphasizing engineering design; (ii) incorporation of important and developmentally appropriate mathematics, science, and technology knowledge and skills; and (iii) promotion of engineering habits of mind. Moore et al[12] have listed the following outcomes as key indicators for a quality K-12 education: (1) Processes of Design; (2) Apply Science, Engineering, and Mathematics; (3) Engineering Thinking; (4) Conceptions of Engineers and Engineering; (5) Engineering Tools; (6) Issues, Solutions, and Impacts; (7) Ethics; (8) Teamwork; and (9) Communication Related to Engineering. As such, the Hampton Roads-Partnership for Algebra (HR-PAL) project (a National Science Foundation Math Science Partnership Start-funded project) was used to introduce an algebra-based framework as a way to build the necessary engineering skills at K-12. The pilot partnership was comprised of Hampton University, two community colleges, and three public school districts. The HR-PAL framework addresses the key engineering education indicators stated above in developing problem solving and algebraic thinking skills at K-12 level, using a basic engineering approach, namely 'system analysis', in solving word problems.

The 'system analysis' approach is introduced to K-12 teachers as a methodology to analyze and solve word problems and also, to develop new word problems, both determinate and open-ended. The concept of using 'system analysis' for problem solving in K-12 education is novel and the authors did not find any reference to its prior use. In this project, this approach is practiced through teachers' professional learning communities, namely, teachers' circles and summer institutes as part of professional development. Teachers' circles are moderated open discussions based on a model developed by the American Institute of Mathematics (AIM) (www.teacherscircle.org). In this type of learning community, secondary education teachers of different backgrounds and areas of specialization can interact with other professionals. In this project, engineering faculty developed application-based problems, moderated the sessions, and introduced the 'system analysis' approach for solving the problems algebraically. After the teachers became familiar with applying 'system analysis' to the solution of determinate problems, simple open-ended problems were tackled during the teachers' circles which were held during the academic year. During summer, engineering design problems, that require simple theory and algebraic equations, were introduced and solved during a two-week summer institute using 'system analysis'.

The 'system analysis' approach presented to teachers considers the definition of a system as a composition of components which interact with each other to produce output(s) based on inputs. The best way to define the behavior of a system is to define the variables which govern the behavior of the system. Some of these variables are independent (or input) variables while others are dependent (or output) variables, whose values depend on the values of the independent variables. To comprehend how a system behaves is to express mathematically how the values of the independent variables affect the values of the dependent variables. The resulting mathematical expressions are referred to as model equations for the system. The analysis of engineering, technology, and physical systems is possible by using those model equations. Therefore, the 'system analysis' problem solving steps for the word problems are summarized as:

1. Define the system by way of drawing a simple diagram to describe the problem.
2. Specify all the system variables (V= number of variables).
3. Generate a mathematical description based on theory and simplifications, determining all the independent equations (E = number of independent equations).
4. Determine the number of degrees of freedom (d.f. = V-E).
5. Define a determinate or indeterminate (design) problem by specifying as many pieces of information as the number of d.f. or less, respectively.
6. Develop the solution algorithm based on equations determined in step (3) and the information specified in step (5).
7. Produce a numerical solution of the problem

The above steps can be illustrated using a simple algebra problem. Consider that the length of a rectangular-shaped backyard is 8 feet less than twice the width. If 260 feet of fencing is needed to enclose the yard, find the dimensions of the yard.

Step 1: Defining the system using a drawing.

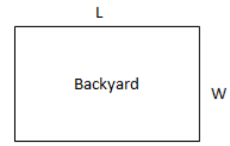

Figure 1: Picture to describe the algebra problem

Step 2: Specifying the system variables.

There are 3 variables {perimeter (P), length (L), width (W)} (V=3)

Step 3: Generating a mathematical description based on theory and simplifications, resulting in independent equations.

The perimeter is 2(L+W) based on given problem geometry (E=1).

Step 4: Analyzing the system to establish whether it is determinate or indeterminate.

Establishing whether the problem is determinate or indeterminate is based on the number of degrees of freedom (d.f.) in the system. If d.f. = 0, it is a determinate case and it means there is only one solution. However, if d.f. > 0, there may be several alternative solutions, which implies a design case. The degrees of freedom are based on the difference between the number of variables and independent equations.

Therefore, d.f. = V-E=3 – 1 = 2.

Step 5: Define the problem by specifying the variable(s).

In this problem, two extra pieces of information are to be specified to define a determinate problem. These will result in two additional independent equations thus, reducing the degrees of freedom to zero. Therefore, there is only one solution to the problem. The perimeter and the relationship between L and W are specified.

Perimeter, P = 260.
Length, L = 2W – 8.

Step 6: Develop the solution algorithm in terms of equations and variables.

P = 2(L+W) = 2(2W – 8 + W) = 2(3W -8) or W = (P + 16)/6

Step 7: Produce a numerical solution of the problem

W = (260 + 16)/6 = 46-ft
L = 2W – 8 = 84-ft

In case of structuring an open-ended (indeterminate or design) problem one can specify one piece of information leaving the degree of freedom at one. This will allow the production of alternative solutions.

The teachers' circles and the summer institute had the goal of enhancing the problem-solving and critical thinking skills of secondary education teachers by having them work on the algebra problems. It is hoped that the teachers will continue to introduce and emphasize these skills in their classrooms encouraging their students to use them effectively. The other premise of the approach is that skills cannot be developed in a passive manner; the learner has to actually do the work (active method of learning). This approach emphasizes a path to algorithmic reasoning and integration of mathematics with other subjects to infuse real-world problems in teaching algebra. Also, the method establishes a starting point for solving problems, which is often times the complaint of students (I don't know where to start), not only in algebra but in engineering as well. Therefore, this is a systematic approach that provides a roadmap to the problem-solving process, by which the reasoning activity is streamlined and generalized. This method may also be employed to demonstrate to the students how to formulate either word problems or a design basis. Additionally, it will help the teachers to demonstrate to their students how to switch from rote memorization to critical thinking.

Outcomes and Discussion

The HR-PAL project approach was piloted from 2011-2013 with mathematics, technology, and art secondary education teachers. During the two years, a total of 82 teachers participated in the teachers' circles, and 44 in the summer institutes. Three teachers' circles were held per academic year as well as one 2-week summer institute. At the beginning of the project, the first participants of teacher circles were asked about the challenges in algebra education and the following were the general responses in no particular order:

- Reading of word problems.
- Writing algebraic equations from a written statement (formulating equations from word problems).
- Variable manipulation.
- Number sense.
- Visualization.
- Plotting/graphing functions and interpretation.
- Meaning of slope and intercept.
- Exponential/logarithmic functions.
- Apply concepts learned in algebra to engineering and science.
- Algorithmic thinking and solving multiple step functions.
- Solving equation with mixed fractions and rearranging equation to solve for one variable.

Initially, word problems were provided to the teachers to receive feedback on the perceived level of difficulty, so that the questions could be calibrated with wording improvements. During the first year, 'system analysis' was not introduced in teachers' circles; therefore, the focus was mainly on determinate problems until the summer institute where two engineering design problems were introduced and the 'system analysis' method was used to solve them. However, in the second year, 'system analysis was introduced during the teachers' circles and it helped to enhance the teachers' motivation during the summer institutes. The first week of the summer institute focused on a truss bridge design problem and the second week on a shipping terminal design problem among other activities. These problems were presented with examples and the teachers were guided through the 'system analysis' in teams of mathematics, technology, and art teachers.

After solving the design problems, the teams had to develop problems for their classroom implementation. Below are examples of what the teachers planned to do in their algebra classrooms as well as in technology courses.

Example #1 – Adapted from the shipping terminal design

You need to order laptop tables for a new computer room. The laptop tables are 6.5 ft by 2.5 ft. One person can sit at the short end and three people can sit along the longer side as illustrated in Figure 2. The square footage of the new computer room will be 650 ft^2. You want to seat as many people in the room as possible. You need to determine:

- How many tables to order?
- The arrangement of the tables.
- The dimensions of the room.
- The number of people the arrangement will accommodate.

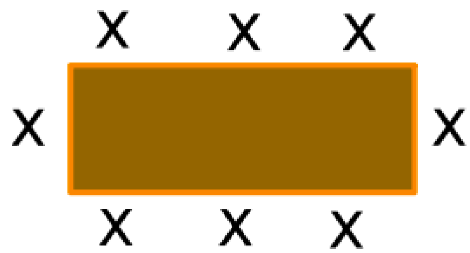

Figure 2: Computer table sitting arrangement

Example #2 - Adapted from the bridge design problem

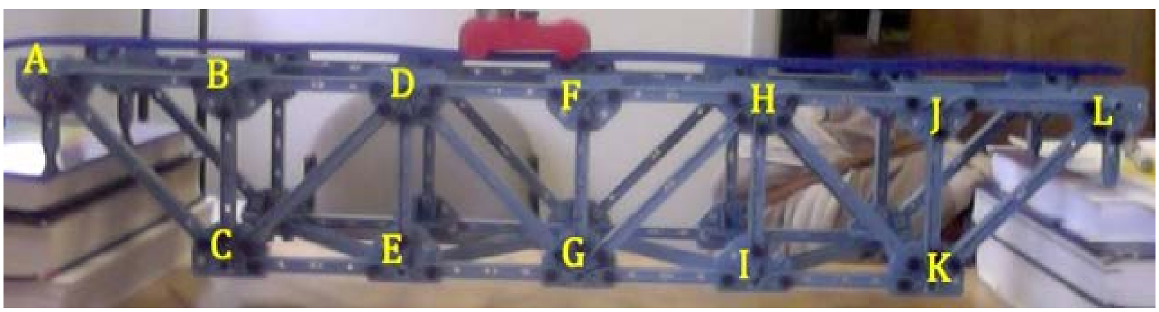

Figure 3: A sample truss bridge

Refer to the bridge diagram above (figure 3). All vertical line segments have a length of 1 meter. All diagonal line segments have a length of $\sqrt{2}$ meters. There are two types of piping that can be cut to create the needed segments for the bridge. The silver pipe is 24 meters and the gray pipe is 23 meters. It is not possible to combine the different pipes. Which one of these pipes could be used to create the bridge and why?

Example #3 – Adapted from the shipping terminal design problem

Hampton M.S. students want to put on a dance. The students have been asked to design the layout based on the following constraints:

- The cafeteria is 40 by 70 square feet.
- The DJ they hired needs 4% of the floor space.
- The PTA will run a snack area and they need 5% of the floor area.
- Fire regulations require 12 square feet for each person in attendance.

- The dance floor should be 25% of the floor space.
- Tables are 3 by 5 but need a space of 1.5 times the dimension for walkways.

Level 1 Questions
- How much area will be taken up by the dance floor? By the DJ? By the snack area?
- What is the area that one table will take up?
- Based on your answer, how many people could attend the dance and still meet fire regulations? (assume 25 tables)

Level 2 Questions
- How much space is available for tables? How many tables would fit in the space?
- If they sell 200 tickets, will they still meet fire code?
- They spent $500 on the DJ and decorations. How many tickets must they sell at $3.00 to make a profit?

Level 3 Questions (a)
- Suppose the electricity went out and the dance had to be moved to the gym of the elementary school. The gym is 65 by 50 square-ft. Assuming the same constraints, how many tables will they be able to fit in the gym and consequently how many tickets will they be able to sell?
- If the tickets are $3.00, how much money will they make?

Level 3 Questions (b)
- The regular price of each ticket was $5.00. Students were given a 50% discount in exchange for 25 Eagle tickets. If the money from ticket sales totaled $1200, and 300 tickets were sold, how many students received the 50% discount?

Sample of 'System Analysis' specification of all the system variables and generating a mathematical description based on theory and simplifications for Example #3 is as follows.

Identify Variables:
- A = Area of Venue
- L = Length of venue
- W = Width of venue
- DJ = Area of DJ Booth
- SB = Area of Snack Bar
- DF = Area of Dance Floor
- a = percentage of A occupied by DJ
- b = percentage of A occupied by SB
- c = percentage of A occupied by DF
- Ta = Number of Tables
- L_T = Length of a table
- W_T = Width of a table
- S = space factor for walkways around tables
- Ti = Number of tickets sold
- M = Gross Money collected
- P = Ticket price
- D = percentage discount on tickets for the students
- F = Fire regulation

Number of variables = 18

Identify Equations:

- A= L x W
- DJ = a•A
- SB = b•A
- Ta= A – (DJ + SB+DF) / ((L_T x W_T)• S)
- DF= c•A
- Ti = (A-(DJ+SB+DF))/F (maximum)
- M = P• Ti

Number of independent equations = 7 (New equations will be added according to the problem statement, like a=0.04, b=0.05, etc.) Therefore, number of degrees of freedom is 11 (from the difference between the number of variables and independent equations).

Thus, the system analysis makes the problem clear and comprehensible, emphasizing the meaning of the variables in the system as well as the interaction between them. Based on this analysis, the teachers will be able to create their own problems. They will comprehend that one can structure either determinate or open-ended (design) problems once they determine the degrees of freedom in the system through system analysis, and subsequently assigning numerical values to as many variables as needed by the type of problem they intend to present. Additionally, this approach gives a powerful tool to the teachers to teach an effective problem-solving approach to their students. The method, also, opens the path to the introduction of the students to the engineering approach of reasoning and algorithmic thinking, which is indispensable for the use of computers.

Example #4 - Adapted from the bridge design problem

Structural Engineering for a technology class: Teams work to determine superior engineering solution as they conduct research and then model and test a truss bridge to determine the greatest weight the bridge can hold. The bridge will be destructively tested and cannot exceed 3 inches in height, must be 3 inches wide. Teams are limited to 20 feet of 1/8 inch by 1/8 inch of balsa wood.

The impact of this approach has been primarily evaluated by feedback through surveys from the teachers' circles and the summer institutes. The survey results indicated that the teachers exhibited significant changes in their confidence in demonstrating examples on the use of critical thinking skills, and providing opportunities to solve problems relating to real life situations. Some participants reflected on how their summer institute engineering design project experience will impact their teaching based on their subject area; for example, the art teachers said they will improve their teaching based on the bridge design project to introduce a systematic sequencing of tasks that need to be completed and will use more visuals for problems. The mathematics teachers said that they can now introduce and solve determinate and open-ended problems in the classroom. Additionally, a symposium was held 9 months after the first summer institute to discuss: 1) how the teachers were using 'system analysis' in their classrooms; 2) how they were sharing the knowledge with their colleagues who did not attend the summer institute; and 3) the challenges they were facing from the students. Some of the teachers said they could use this approach in the classroom and the others were already working on training other teachers in understanding the 'system analysis' approach. Work is on-going with the school systems to involve more teachers as well as to get feedback on the progress of classroom implementation.

Conclusion

The focus of the paper is on how engineering educators introduced the concept of 'system analysis' to algebra and technology teachers as a methodology to analyze, solve word problems, and develop new word problems that maybe either determinate or open-ended. The concept was practiced during secondary school professional learning communities, namely teachers' circles and summer institutes. After the teachers became familiar with applying 'system analysis' to the solution of determinate problems, simple open-ended problems were tackled during the teachers' circles held in the academic year. Engineering design problems with simple theory and just algebraic equations were introduced and solved during a two-week summer institute that included mathematics, technology, and art teachers. The authors' goal in using this method was to help teachers in introducing the students in algebra classes to engineering thinking through the existing courses in their curriculum to make core courses relevant to the applications in their everyday lives. It is the authors' opinion that it may be more effective to use this approach rather than introducing new engineering courses at K-12 level.

Acknowledgements

The authors wish to acknowledge the support provided for this work through the National Science Foundation MSP-Start program under Grant #1050387.

References

1. Farmer, C., S. Klein-Gardner, and L. Nadelson, "Standards for Preparation and Professional Development for Teachers of Engineering," ASEE, 2014.
2. Author, "Engineering by Design," Available at http://www.iteea.org/EbD/ebd.htm
3. Author, "Project Lead The Way(PLTW)," Available at https://www.pltw.org/
4. Johnson, G., "Project Lead the Way: Synergy of Colleges and Universities with Secondary Education," ASEE Annual Conference Proceedings, 2003.
5. Author, "Meeting the STEM Workforce Demand: Accelerating Math Learning Among Students Interested in STEM" Business Higher Education Research Brief (2011) Available from http://www.bhef.com/sites/g/files/g829556/f/brief_2011_accelerating_math.pdf
6. M. Lord, "Hands-on-Mathematics: Algebra, Trigonometry, and Calculus tailored for engineers help boost retention and student success" ASEE Prism, September 2012, 45-47.
7. Wang, Y., J. Lian, and Y. Yang. "*Interactive Math Learning for STEM Students*" ASEE Annual Conference Proceedings, 2012.
8. Clotfelter, C. T., H. F. Ladd, and J. L. Vigdor. "*The Aftermath of Accelerating Algebra: Evidence from a District Policy Initiative*," National Center For Analysis Of Longitudinal Data In Education Research, 2012.
9. Author, "*Why We're Behind: What Top Nations Teach Their Students But We Don't*", Common Core, December 2011.
10. Author, "Next Generation Science Standards (First Public Draft)," The National Academy of Sciences, Achieve, The American Association for the Advancement of Science, The National Science Teachers Association, 2012.

11. Sztajn, P., K. Marrongelle, P. Smith, and B. Melton. **"***Supporting Implementation of the Common Core State Standards for Mathematics: Recommendations for Professional Development*," The William & Ida Friday Institute for Educational Innovation at the North Carolina State University College of Education, 2012.
12. Moore, T. J., et al, "A Framework for Quality K-12 Engineering Education: Research and Development" Journal of Pre-College Engineering Education Research 4:1, 2014, 1–13.
13. Katehi, L., G. Pearson, and M. Feder, "Engineering in K-12 Education: Understanding the Status and Improving the Prospects," The National Academies Press, 2009.
14. Monfort, D., and S. Brown, "Secondary Students' Conceptions of Engineers and Engineering: A Case Study Approach," ASEE Annual Conference Proceedings, 2010.
15. Klein, D. et al "*The State of State Math Standards,"* Report by Fordham Foundation, Washington, D.C., 2005.

Otsebele Nare

Dr. Otsebele Nare is an electrical engineering associate professor in the school of engineering and technology at Hampton University, Hampton, VA. His research interests include system level synthesis design methodologies, integrated energy systems and integrative STEM education. He received D.Eng degree in electrical engineering from Morgan State University (2005) in Baltimore, MD. He is a member of ASEE and IEEE.

Jale Akyurtlu

Dr. Jale Akyurtlu received her BS in chemical engineering, Middle East Technical University, Ankara, Turkey, 1967; MS in chemical engineering, Middle East Technical University, Ankara, Turkey, 1969; Ph.D in chemical engineering, University of Wisconsin-Madison, Madison,, WI, 1975. She has been a Professor of chemical engineering since 1993 at Hampton University, Hampton, VA 23668; and has been an Endowed University Professor of Engineering since 2000. Her research interests are in modeling of chemical reactors; catalytic and noncatalytic gas-solid reactions; above topics related to general energy and environmental research; undergraduate education in nanotechnology and engineering education in general. She is a member of AIChE.