Infusing Informed Engineering Design Pedagogy in K-12 Math and Science Courses

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Abstract

The paper describes how K-12 Engineering can be an important pedagogical approach in mathematics and science courses. K-12 Engineering is examined in a STEM context with examples provided. Building on sponsored research, a framework has been developed using informed engineering design and results from several studies indicate positive improvement in student content knowledge and disposition towards STEM and STEM careers.

Introduction

For the past two decades there has been a significant effort in the United States to improve science, technology, engineering, and mathematics (STEM) education. The acronym has evolved from MST, to SMET, to STEM. Numerous reports from government agencies (NSF, DOE, NASA) have been insistent on the importance of preparedness in the STEM fields. For instance, a recent report to President Obama noted that it was of the upmost importance for the education system to instill strong foundation in STEM in our students as our nation's students are the future innovators and leaders in the development of new discoveries and advancements in the ever so important STEM fields, as energy, healthcare, security, and the environmental sciences. However, many are concerned that our education system is not producing enough thinkers to fill positions in the STEM fields. Our nation's students need these STEM skills to become capable workers and successful members of their community.

While a great deal of focus has been placed on mathematics and science preparedness, little attention has been on including or incorporating engineering ideas and themes into the schools. Nonetheless, using engineering as a teaching pedagogy is a unique and innovative way to help teach STEM skills within K – 12 classrooms, as well as peak interest in the STEM careers.

K-12 Engineering

What does engineering mean when it is included in STEM? How is it different than the practice of engineering in the business world? One way to begin to understand engineering in this context is to contrast the differences between math, science, engineering and social science/humanities. These differences are displayed in Table 1 (Burghardt, 2007). For instance, science is the study of the natural world, a discipline engaged in discovering the whys and wherefores of natural phenomena. There is a process for this investigation, scientific inquiry, in which a hypothesis is posed and logical investigations are undertaken to confirm or deny the hypothesis. Mathematics has its own philosophy and patterns, often used by engineers and scientists to model designs or to represent natural phenomena, such as Newton's second law of motion ($F = m a$). There are rules of mathematical analysis and theorems, which allow us to manipulate such equations. A publication by the National Research Council, *Helping Children Learn Mathematics* (2002), discusses the big ideas and habits of mind needed to be mathematically successful. The social sciences and humanities provide an entirely different view of the world, a world shaped by human perceptions and understandings. For instance, a novel or a political or social event can by analyzed from many different perspectives. These are thumbnail sketches, but they can highlight the differences between disciplines and help in thinking about the overarching themes that define engineering, noun and verb.

Engineering	Science	Mathematics	Social sciences and humanities
Study of the human-made world	Study of the natural world	Study of mathematical constructs	Study of human mind and perception
Engineering design	Scientific inquiry	Mathematical analysis	Rhetoric and criticism
Iterative design process, optimum solution	Hypothesis testing and evaluation	Theorems, proofs, rational constructs	Eclectic methods, comparative values
Artifact produced	Theory confirmed	Theorem validated	Opinion rationalized

Table 1 Comparison between different fields of thought

Engineering is able to uniquely connect all three disciplines. In creating the human-made world, engineers must use knowledge from science, mathematics and social sciences and humanities. In contrast to scientific inquiry and mathematical analysis, engineering design does not seek a unique or correct solution, but rather seeks the best or optimum solution after a variety of factors are weighed, such as cost, materials, aesthetics, and marketability. The design process is iterative, creative, and nonlinear. The solutions are tempered by our societal values. Hence, the optimal solution for one person may not be the optimum solution for another. Because we can bring our values to our design solutions, engineering design can be a very engaging pedagogical strategy.

Engineering becomes a way of understanding the human-made world, how it was created, how it functions and how it might be changed. Engineers realize that what has been made can be improved. Even if it were optimum at a moment in time for the specifications and constraints that were imposed, new technologies, new opinions, new perspectives allow for different solutions. This is a very empowering feature of engineering and this is in significant contrast to scientific and mathematical understandings, where hypotheses and theorems may be refined, but in the main they remain unalterable.

Engineering design is not trial-and-error gadgeteering. Engineers use their knowledge of science and engineering science to understand what is happening physically, their use of mathematics to create models that may be analyzed, and their understanding of prior technological solutions so they can innovate. Then they create design solutions. This is in contrast to the process used by inventors who may gadgeteer, arriving at a workable solution that they can patent or manufacture. The use of modeling, with its inherent predictive analysis, is one of the significant differences between engineering and technology education, and engineering and art.

Engineering design and the design process are inherent to engineering, as the roots of the word engineer are linked to the design process. But what of concepts like optimism and creativity? There are engineering habits of mind (visualization, creativity, connecting science, mathematics, social sciences and humanities, optimism, how things work, systems thinking) and engineering practice (engineering design including optimization, specifications and constraints,

Engineering (the verb) provides all students with problem-solving strategies for understanding the human-made world and for applying concepts in mathematics, science and social science and humanities. Engineering (the noun) can refine these skills for students interested in further exploring the human-made world. In terms of K-12 education, the habits of mind and engineering design would be part of all students' education, K-12, the study of the human-made world.

According to the National Academy of Engineering (Katehi, Pearson & Feder, 2009) applying Engineering in K – 12 classrooms is still a rather new subject and its integrated into classroom has been somewhat informal and without a widespread application as of yet. With the advancement of the common core math standards that argue for real life examples , and in anticipation of the Next Generation Science Standards that include engineering specifically in the standards, engineering is an important part of STEM learning. An important part that is much less well developed than its math and science STEM counterparts.

Engineering as a Teaching Pedagogy

As the focus on STEM learning increases, so with it does the need to increase the use of innovative ways to enhance STEM teaching in the classroom. Many cite using the concept of engineering as an approach to increase STEM performance of students in grades K- 12. Engineering is often synonymous with the word design, and it can be defined as "design under constraint" (Wulf, 1998). According to NAE (2010), engineering design involves a process from identifying a problem, specifying the solutions requirements, to generating and testing a solution and then evaluating alternatives, in order to optimize a final design. Thus, using engineering as a teaching pedagogy is can be considered a hands-on-learning experience that is ideal to provide the context for foundational STEM concepts (Carlson & Sullivan, 2004). This in turn has the potential to focus on reality, collaboration, and creativity of students working together to design a project or solve a problem (Brophy et al., 2008). When working in this manner, it allows for the potential to make science and math more relevant for students, while increasing interest and awareness of STEM careers at the same time (Katehi, Pearson & Feder, 2009).

Accordingly, engineering is a natural way to connect STM in K – 12 classrooms to integrate their knowledge in a contextualized manner. When the National Academy of Engineering (Katehi, Pearson & Feder, 2009) reviewed K-12 engineering education they cited engineering could be used as "a catalyst" to integrate STEM within the schools and note that infusing engineering ideas, activities, projects etc into already existing STE curricula is direct and uncomplicated way to make STEM more integrated. They also noted that this integration of engineering and technology has the potential to increase student motivation and achievement, as well as provide a real-world context. Roehrig, Moore, Wang, and Park (2012) also comment that using engineering in the K-12 curriculum aligns with the interdisciplinary problems of the 21st century, as well as well provide the authentic learning experience to engage students in STEM. When using engineering design, students will need to use mathematical reasoning and content knowledge to create dynamic and effective learning environments. The thought is if students are taught science and mathematics content as they solve engineering problems or using engineering design, they will learn and retain the content easily because they are taught in a real-world context that is engaging.

While there is still a paucity of research in the area, some preliminary work has been completed to identify the benefits of infusing engineering design into the STM curricula. Koch and Burghardt (2002) explored the use of using engineering design in elementary school math and science units as part of a STEM, then MST, graduate program in elementary education. Three themes emerged, which have remained consistent with further investigations. These themes included (1) changes in teachers' own perceptions of their abilities to create student centered classrooms where each student group has control of the direction of their learning; (2) changes in students' attitudes towards mathematics, science and/or engineering/technology and in their understanding of the materials relating to the design process; (3) changes in the ways in which children with special needs engaged in group work and contributed to the final design project.

Atkins and Burghardt (2006) investigated a connected mathematics and engineering design curriculum (construction of a food dehydrator) in the middle and high school. When dividing the students into quartiles and looking at pre-post test difference, all students showed growth, but the bottom two quartiles showed the greatest gains in performance. A study by Burghardt and Krowles (2006) working with low performing fifth grade students in a remedial mathematics class, indicated the use of engineering design pedagogy in a geometry unit provided dramatic shifts in mathematics content knowledge, from pre-assessment average of 18% to a post – assessment average of 88%. There were equally dramatic improvements in student attitude towards mathematics.

Lachapelle and Cunningham (2007) utilized an engineering curriculum at the Museum of Science in Boston to determine its effects of student learning of mathematical and science concepts. Although there was no comparison group, students who participated in the curriculum showed significant growth in both their science and engineering scores. In another design based science curriculum Klein and Sherwood (2005) followed schools over three years to see if mathematics and science scores rose, and found that students in the experimental group had statistically larger increases on assessments of science knowledge and concepts.

A recent study of an middle school technology curriculum that used an engineering design found that students' mathematical content knowledge and attitude toward mathematics showed significant increases after participation in the curriculum and significantly higher post-test scores than control group students, as well as a shift in student attitudes toward mathematics (Burghardt, Hecht, Russo, Lauckhardt & Hacker, 2011). While the research base is still limited, infusing engineering into other subjects appears to be on the forefront of STEM education.

Informed engineering design pedagogy

Informed design (Burghardt and Hacker, 2004) is a pedagogical approach that engages students in the development of knowledge and skills relevant to the design challenge at hand. Instead of trial-and-error problem solving, students apply their understanding to create *informed* design solutions. Thus, students are motivated to learn in a just-in-time manner through explicit learning events called knowledge and skill builders (KSBs). KSB's provide structured inquiry learning about key STEM concepts that underpin the design challenge. A recent project, WISEngineering, funded by the Bill and Melinda Gates Foundation, investigated using informed design engineering and digital fabrication in seventh grade math classes. WISEngineering built from the informed engineering design pedagogical approach to provide an explicit design cycle to guide students' design projects (Figure 1):

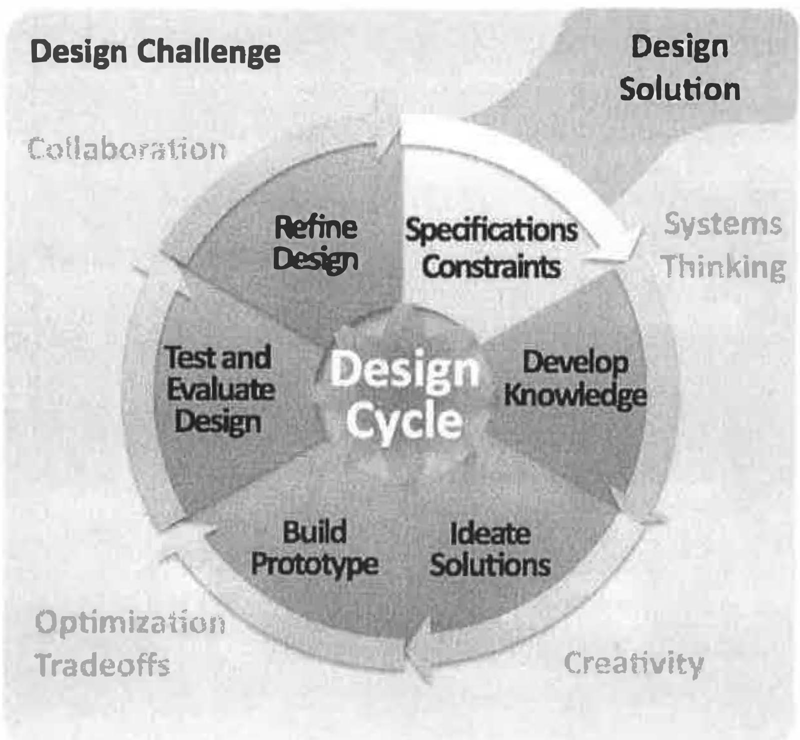

Figure 1. Informed Design Cycle used in WISEngineering projects

The approach includes the following elements after the design challenge is set. The challenge itself should connect to interest to the students, often framed in socially relevant ways. For instance, in WISEngineering, one of the challenges had to do with creating a scale model of a community center for the community they were living in. Students were interested in different aspects of community centers, such as temporary housing, cooking facilities, and exercise rooms.

Once the challenge is created, here are the various elements of the informed design process.

Clarifying design specifications and constraints – design challenges have particular specifications and constraints to consider in developing a solution. Typical constraints emphasized in projects include time or cost. Specifications can emphasize particular concepts to be learned during the project and require students to develop and apply their understandings of these concepts.

Develop Knowledge – A consideration of the specifications and constraints lead to investigation or inquiry into related concepts needed to solve the problem. The use of KSBs are included in this section.

Ideate Solutions – Ideating Solutions is not simply brainstorming, rather, ideation encourages students to develop multiple, *appropriate* solutions to the task at hand.

Justify Optimum Solution—Students need to apply their knowledge to provide justification for one model over another. The use of predictive and representational *modeling* is included here.

Build Prototype – Selecting from their potential solutions, students construct virtual models or real-life prototypes.

Test and Evaluate Design – Students test designs and evaluate whether they satisfy the project criteria.

Refine Design – Based on tests, students revise designs to optimize their solutions.

These phases are not considered to be linear, rather, students are encouraged to revisit steps iteratively, revising design solutions with the aid of repeated research and investigation. This explicit representation of an informed engineering process also includes key engineering habits of mind. By using this representation to guide the student experience, the aim is to foster a classroom environment in which students will be aware of and involved in systems thinking, use creative thinking and problem solving skills, work to optimize and consider tradeoffs in design, and collaborate with classmates.

Decision Rules for Interconnecting Informed Engineering Design Pedagogy into Math and Science Units

The design of experiments is important in the practice of science and while it is possible for students to design science experiments, in practice the experiments are prescribed. Thus, there needs to be a different approach to introducing design, one in which the essence of the existing experiment remains and it is transformed into a knowledge that must be applied to the design challenge under consideration. Of course, from a teacher perspective, using design provides an opportunity to use design as an assessment strategy, requiring that teachers understand specifications and constraints and multiple solutions, no one correct answer, but the assessment of the process. Creating design challenges that allow for multiple solutions which engages students' creativity, accomplished with the resources in the classroom, is in itself demanding. Not all science topics are amenable for design solutions, but many are.

The Math Infusion in Science Project (MiSP) investigated infusing mathematics in eighth grade science curriculum to determine if doing so would improve student understanding of math, as demonstrated on project and standardized state exams. The project found that the methodology is very effective as evidenced in a study of about 700 experimental and 700 control students in the phase I analysis as evidenced by statistically significant improvement in student performance on NY State standardized exams in math, as well as on project affective and content assessments. The decision rules of MiSP for math infusion in science have been adapted in the creation of math and science units using engineering design pedagogy.

As can be seen in Table 2, there are various ways to systematically use engineering design in science and mathematics classes.

- Each subject (math and science) maintains its own perspective
    1. Informed Engineering Design is *infused* into various math and science units
    2. Math and Science remain the primary subjects.
- Informed Engineering Design Pedagogy is introduced multiple times within different science and math lessons to allow for transference of understanding of concepts
- The sequence of science and of math topics is determined by the teacher/school.
- The Math topics, the Science topics, must be challenging for students and key for later understanding of more complex math or science concepts;
- Informed Engineering Design fits naturally within the science unit or math unit;
- Science units, or math units, must be taught in an inquiry based way and be of long enough duration to allow for students to engage in hands-on activities (typically at least a week long.)
- Teachers must receive professional development in both content and pedagogy to teach math infused science lesson
- All lessons must be aligned with the Common Core Math Standards and the emerging Next Generation State Standards to assure the lessons have district and school relevance and face validity.

Table 2: Decision Rules for Informed Engineering Design Pedagogy into Science and Math

What Does It Look Like?

In a seventh grade science class students are studying genetics. For middle school students learning about themselves and how they inherited traits they have can be very engaging. A design challenge is created where student teams need to design and construct a monster family that demonstrates how genes are passed from parent to offspring. The specifications are: one, that each member of your monster family must have five genes; that four of the five genes must have a dominant and recessive allele, as well as a symbol for each; that one of the five genes must demonstrate co-dominance; that each phenotype must have a genotype symbol; that the baby monster must have genes from both the mother and father monster; and that Punnett squares are used in order to determine the probability of your baby monster inheriting a certain trait from the parent monsters. The students use recycled materials to create the monsters, e.g. plastic containers, feathers, cotton balls, colored paper, paper clips, so the material costs are minimal. The science teacher needs to learn how to support design activities where there can be different solutions, but does not need to learn new science content. So there are pedagogical and classroom management challenges, but not content challenges.

The Community Building Challenge in WISEngineering is a two-week design project unit that focuses on Common Core Mathematics Standards for learning in mathematics including geometry, ratios and proportions, and expressions and equations through engineering design. The CBC challenges students to create a community center dedicated to serve the people of their town. They design an original model that must meet certain criteria (i.e. specifications and constraints) wherein the building must use at least three geometric solids with a volume between volume between 150cm^3 and 250cm^3 and that the surface area of the model structure must be between 170cm^2 and 350 cm^2 while addressing the challenge. Cost is also a factor, as each geometric shape has a cost associated with it. Specific math learning goals are addressed, including the recognition of three-dimensional shapes, volume and surface area calculations for both two-dimensional and three-dimensional shapes, as well as calculating decimals and percents from obtained data (objectives 7.G 1-7.G6 in the Common Core Standards for Mathematics).

Pre and post assessments were administered for the Community Center project. Each activity emphasized different math skills. Results are presented for the overall sample as well as for differing NJ ASK proficiency levels. Paired samples t-tests were used to determine whether students' showed a statistically significant improvement from pre to post assessments. All t-tests were conducted with an α=.05 significance level. The Community Center assessment consisted of eleven questions measuring students' knowledge of volume, surface area, and three-dimensional shapes. In the overall sample, students' scores on this unit's assessment increased 5.1 percentage points. This increase was statistically significant, $t(81)= 2.44, p<.05$. Students classified by the 6th grade NJ ASK math test as "Proficient" improved their scores on this assessment by nearly 7 percentage points; students classified as "Advanced Proficient" improved their scores on this assessment by 9.6 percentage points. However, students classified as "Partially Proficient" displayed no statistically significant growth on this assessment.

Conclusions

Several conclusions can be made: one, the informed engineering design process has been shown to be an effective pedagogical strategy in math and science classes; two, the decision rules for infusion have been successfully implemented and demonstrated; and three, the use of engineering design as a pedagogical strategy is viable and promotes deeper student learning and engages student affectively in their learning experiences.

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