Advances in Engineering Education

SUMMER 2012

Model Wind Turbine Design in a Project-Based Middle School Engineering Curriculum Built on State Frameworks

STEVEN D. COGGER
Reading Memorial High School
Reading, Massachusetts

and

DANIEL H. MILEY
West Middle School
Andover, Massachusetts

ABSTRACT

This paper proposes that project-based active learning is a key part of engineering education at the middle school level. One project from a comprehensive middle school engineering curriculum developed by the authors is described to show how active learning and state frameworks can co-exist. The theoretical basis for learning and assessment in a project-based curriculum is presented as a more favorable approach to teaching engineering in middle school. We address the unique issues of middle school students and how they engage the engineering process. We conclude that project-based active learning is integral in a successful engineering education program for middle school students.

Keywords: middle school engineering, project-based learning, state engineering frameworks

INTRODUCTION

The Andover Public School district started teaching engineering as a stand-alone curriculum in one middle school in 2005. Due to the success of the pilot curriculum the program was implemented sequentially in the town's other two middle schools starting in 2007 and 2008. Engineering is a one-quarter (9-week) course that all students take in 6th, 7th, and 8th grades as part of their exploratory rotation with art, music, and health. The engineering program is popular with the students and has been supported by parents and the community. The curriculum is designed to provide enjoyable, challenging, and hands-on learning experiences for students that allow them to apply their science and mathematics knowledge to the theory and methods they learn in engineering.

We have developed a hands-on, project-based curriculum with explicit ties to the state frameworks. The Massachusetts Middle School Technology/Engineering Framework [1] represents about 25% of the content in the 8th grade Science and Technology/Engineering test of the Massachusetts Comprehensive Assessment System (MCAS). We have taken an approach to build the standards into a project-based curriculum instead of engaging in transmissive teaching of the framework content. The different projects are designed for each grade level to match the cognitive ability of the students with their knowledge and practice of engineering skills and concepts.

“Engineering: You can do it!” is the theme of the 6th grade curriculum. We start with relatively simple projects where students are introduced to engineering and start to build the foundations of an active, project-based classroom. In 7th grade the theme is “Engineering a Better World”. This theme focuses on issues of energy and environment with two design projects: Wind Turbines and Solar Powered Boats. Our theme for 8th grade is “A Major Design Project”. By the 8th grade the students have had over 60 classroom hours of engineering, so we challenge them with a project where they design and build a radio-controlled vehicle to accomplish a mission that they define.

Stand-alone engineering programs at the middle school level are rare, despite the calls for increased STEM education [2–3], due to a shortage of teachers trained to teach engineering [4], and the perceived time constraints in the existing curriculum [5]. Without exposure to engineering, students are missing the opportunity to learn a vital set of 21st century skills including creativity, the ability to solve problems with unknown outcomes, risk taking, and finding success in failure. Engineering as a discipline and as a pedagogical practice can help students develop these skills while introducing them to the possibilities of engineering as a career. The socio-constructivist aspects of a project-based engineering class fit well with the unique characteristics of middle school students [6], enhancing the prospect of building interest in STEM education at this important stage in their development. Moreover, a classroom focused on project-based, active learning can uncover skills and inspire students who may not perform as well as their peers in a more traditional classroom setting [7].

Recognizing that there is a shortage of trained engineering teachers and the limited time for dedicated in most school calendars, we present our Wind Turbine project as a way of introducing engineering to students within the constraints of time and teacher training. This project can be adapted to science classrooms and can be taught with minimal training due to numerous supportive resources from companies like Kid Wind. The project can be implemented with an initial investment of $250 and a yearly recurring cost of consumable materials of approximately $50 per 100 students.

Engineering and active learning

Constructivism, where students are in charge of their own learning, is an inherent part of a project-based engineering curriculum. The pedagogical grounds of radical and social constructivism as it applies to learning science can also be applied to learning and understanding engineering [8]. We want our students to become learners by developing their own knowledge, rather than knowers, who are told what is important from the perspective of one teacher. Rotjer makes the case "that the constructivist approach is the right educational tool in engineering education for professional practice" [9]. Although this quote is directed at college-level engineering education, its application to secondary education is eminent. Even if middle school students do not become engineers, knowing how to learn by constructing their own knowledge is a lifelong skill.

Engineering embraces socio-constructivist theories of learning developed by Vygotsky [10], where knowledge is created and validated through social interaction. Cheville describes a five-step engineering design process that integrates the Vygotsky cycle where students socially construct knowledge [11]. Students learning design follow the process and the Vygotsky cycle, transforming themselves and their interpretation of knowledge. Design requires a divergent thought process where students manipulate concepts to explore new ideas, allowing the development of multiple possible solutions to the same problem. The social construction of knowledge occurs when students work together and share ideas as they develop solutions to a given problem.

In our projects and curriculum, we introduce the 8-step Engineering Design Process (EDP) per the Massachusetts framework shown in Figure 1 is a modified representation of the process 5-step process defined by Cheville. Both processes stress the iterative nature of engineering; however Massachusetts adds extra steps to the EDP: identification of the need, the development of possible solutions, and the selection the best solution. The extra steps in the Massachusetts EDP are defined in Cheville's process as modeling [11].

We incorporate socio-constructivism and the Vygotsky cycle in our curriculum by pairing students in the design projects so they will share ideas in their teams with other groups formally and informally. In our classrooms, we observe discussions of the design process as the students are constantly engaged during the test and redesign phase. The students actively construct knowledge and build upon their own ideas as well as the ideas of other students during these discussions.

Active learning, project-based learning, and problem-based learning have similar meanings; they are learner-centered and fall under the category of inductive learning [12]. In a classroom

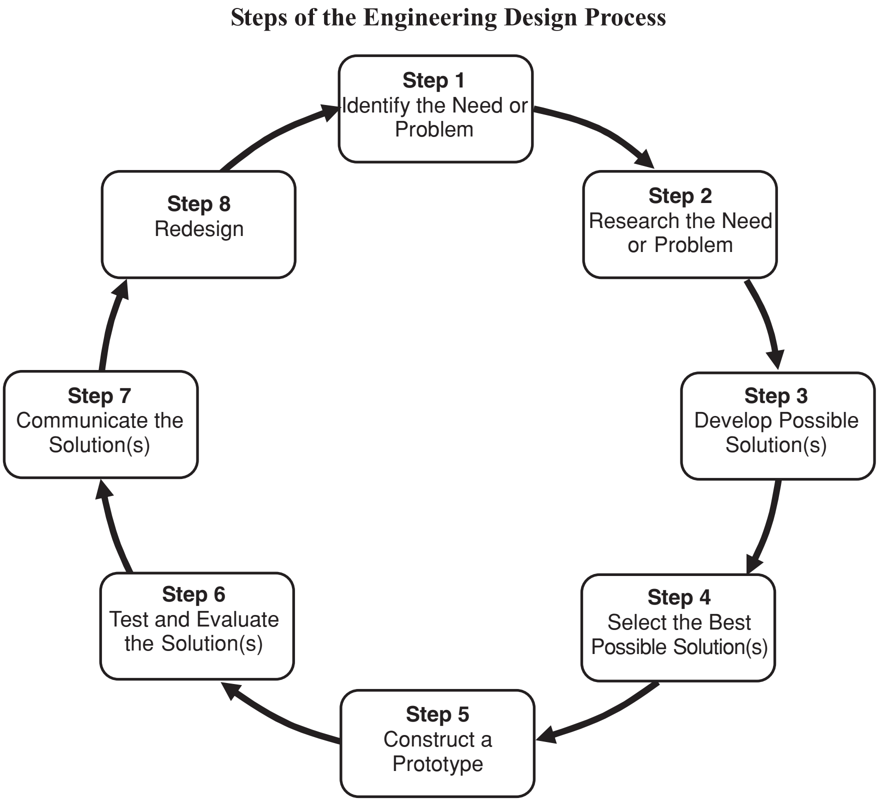


Figure 1. Eight-step Engineering Design Process per Massachusetts Science, Technology and Engineering Framework. Courtesy Massachusetts DESE.

characterized by inductive learning, students are actively engaged and motivated by a perceived need to know rather than being told what they should know.

By solving a problem with a relevant or real-world application using their own ideas, students often see a reason to learn. Although the differences may be subtle, we should make the distinction between project-based learning and problem-based learning. Project-based learning presents students with a task that leads to a final product. In project-based learning, materials and constraints are defined at the beginning, which aids students in achieving the final outcome. Problem-based learning is more open-ended and requires a higher level of student involvement in their learning.

The cognitive abilities of middle school students coupled with their level of math and science knowledge prompted us to take a project-based rather than problem-based approach to the curriculum in the 6th and 7th grade. An additional reason for a project-based approach is that since all students take engineering, the classes constitute a wide range of abilities and motivation. A project-based curriculum provides more structure for students who need it, while letting us offer greater challenges for students who are highly motivated by the subject material. Since we have a three-year program, we shift to a more problem-based activity when our students are in the 8th grade and have developed the skills necessary to undertake more open-ended problems.

Project-based or problem-based learning has been successfully applied in science classes as a way of introducing engineering and the design process to students who do not have a dedicated engineering curriculum [7, 13–15]. Active learning is a way to introduce the design-process and engage students in the subject material, primarily in science classrooms. Doppelt et al. show how Design-Based Learning (DBL) in science can bridge the gap between scripted-inquiry and authentic-inquiry in an attempt to meet the needs and skills of college-level engineering schools [7]. This requires students to utilize the skills of teamwork, design, and hands-on construction in their learning. Kolodner et al. discuss the same ideas as they apply to middle school science, showing how students learn science through design projects while developing skills and confidence in the design process [13].

Engineering in Middle School

In the current research on engineering as part of K-12 education [2, 16–19] we identified three major themes on why engineering should be part of K-12 curriculum: development of technological literacy, development of inquiry skills, and shortages of students pursuing STEM education. The shortage of STEM talent is exacerbated by the under-representation of women and minorities in STEM fields at the secondary and college level. Summaries of current K-12 engineering education discuss the major themes in terms of current teaching practices [20, 21]. Despite the positive research on active and project-based learning, adopting engineering as a separate and objective class in K-12 education is still under discussion, including recent work on common core standards and whether engineering should be a separate standard. The pressure of standardized testing to meet the requirements of No Child Left Behind and the shortage of trained engineering teachers [4] has limited the ability of public education to provide students with engineering in secondary schools. As noted previously, many districts are addressing engineering and the design process by incorporating design activities into existing science classes.

Teaching engineering at the middle school level is essential if we want to increase the numbers of students who ultimately choose STEM careers.

> “Middle school is a critical transition period. It is where decisions are made that will open or close career options. Maths and science are key to careers in engineering and technology. If students decide not to pursue these subjects in high school, they are essentially closing

> doors to certain professions. Thus our main challenge is attracting middle school students to science and engineering" [2, p. 874].

McCuen and Kucner report the reduced enrollment in STEM subject areas in secondary schools due to the perception of the relevance of the subject matter in the lives of the students and the perceived difficulty of the subject. Presentation of theory-driven material in science or math and passive-learning formats has dissuaded students from pursuing STEM education [17]. Lack of relevance in science often leads to students asking, "Why do I need to learn this?"[7]. The implementation of engineering as a pedagogy is seen as a way to engage students by linking the theory taught in math and science to the solving of real problems. Indeed, when students see a use for the theory and witness that they can in fact "do" engineering, we hope that their interest in pursuing STEM subjects and careers will increase.

Perception of engineering as an educational and career choice is an important factor in how to teach it in a K-12 environment. Sohn [22] summarizes global studies of the problems of attracting students into STEM disciplines during their primary and secondary school years. By understanding perceptions of engineering, teachers and administrators can begin to design strategies and curricula to interest students in STEM disciplines. In addition, as we prepare secondary students for future learning in engineering, we should start engaging them at a level where their epistemological beliefs are developing and help them see learning as a transformative process of thought [23].

Middle school students, design, and core engineering concepts

Some may question if students at the middle school level have the requisite skills and domain knowledge in math and science to engage in a meaningful engineering design project. Basic engineering concepts and skills have been identified as defining features that differentiate engineering from applied science [24]. We will highlight these skills and concepts and show how we incorporate them into design projects for middle school students with specific references to the Wind Turbine project. Curriculum must include these skills and concepts, even if they are modified to meet the knowledge of middle school students.

A system is a definition of how components work together to perform a given function. In the definition of systems there are two representations, Structure-Behavior-Functions (SBF) and Emergent Properties (EP). "SBF relates components (structures) in a system to their purpose (function) in the system and the mechanisms that enable them to perform their function (behavior)" [24, p. 122]. Research on children of varying ages concludes that students can recognize the function without understanding the underlying structure. To help overcome the limitations of students, teachers must be ready to point out the limitations of the models, provide information that the students cannot independently discover, and direct students to pursue design challenges by pointing out similarities and differences between familiar objects and the design challenge [24]. The authors conclude that discussing limitations of SBF and allocating enough time for design/redesign cycles will increase conceptual understanding of SBF and modeling.

As an example of how we address SBF in our curriculum, we use the Universal Systems Model (USM) as defined in the Massachusetts frameworks to introduce the elements of a system: Goal, Inputs, Process, Output, and Feedback. Students identify these elements in the turbine project and we discuss the structures, functions, and behavior of the parts in the system. Specifically, we relate these ideas to real wind turbines and point out that the 100 mW output from the model turbine is not a practical idea for commercial use. To help students understand related ideas from similar projects, we carry forward the concepts of the USM to future design projects and build on concepts such as lift and drag, which was introduced to the students in rocket design project completed in the previous year. We also have time, as a dedicated class, to let students engage in numerous design/redesign cycles. Students will typically engage in eight to twelve design/redesign cycles over the duration of the project, allowing ample time to increase their understanding of systems and modeling.

Emergent properties of a system focus on the dynamic interactions among system components. Research has shown that most people, including adults, prefer explanations based a single cause and centralized control; however through simulations they begin to learn about emergent properties where control is decentralized and multiple causes can be considered [24]. This is also true for middle school students. We do not use simulation in our design projects, yet we see through multiple iterations that our students are able to understand how factors like symmetric blade shape and equal blade mass can have a significant effect on the overall system performance of their turbine design. Indeed, without explicit instruction to do so, we have seen students weighing their blades and sanding them down to achieve equal mass before setting them up for testing.

The engineering concept of optimization is the balancing of conflicting requirements and constraints to achieve the best possible outcome, which requires the understanding of multiple variables and tradeoffs [24]. A successful design will require understanding which variables can be controlled to have the greatest effect on the system, and possible tradeoffs that are required to control these variables. Like the systems model, these specific concepts are basic requirements to optimizing a design and require some level of intervention by the teacher in middle school classrooms. The authors cite Silk and Schunn's [25] identification of successive iteration and controlling one variable as a way of developing the idea of design tradeoffs.

Our challenge in the turbine project is to optimize the design to create the highest output power within a given set of constraints. The design includes many variables that are developed by the students during a class discussion at the beginning of the project. Some variables will have little effect on the model, however we do not eliminate them from the initial design decisions that students make. Initially many students design turbines with four or more blades and high blade angles in an effort to catch the wind. Students generally deduce which variables are the most important as they proceed and optimize their designs. With the multiple design iterations and group design reviews, students identify what variables are the most important and how to make design tradeoffs. A consistent problem that occurs at the beginning of the test and redesign phase is persuading the students to only change one variable at a time. On the first day of testing, we guide students in the test process and only allow them to change one variable that day. While this approach may seem overly restrictive in our open learning environment, it is necessary due to the tendency for students to want to start over when the first set of turbine blades does not "work". By emphasizing the idea of changing one variable at a time and thinking about what they have already constructed, we reinforce the concept of testing one variable. To the surprise of many students, they improve their existing design and start to build requisite knowledge of which variables have the greatest effect on the performance of their turbine.

Students also need to learn the engineering skills of representation, drawing and experimentation to fully understand the engineering process. Because students have difficulty understanding the difference between sketches and design drawing, two specific steps are used to clarify this difference. In the Design Brief, we focus on sketching the students' ideas as part of the brainstorming process. We ask students to sketch their ideas individually and then discuss them with their partner to converge on a single idea for the first design. Once their design is determined, both partners draw a 1:1 scale drawing of their turbine blade. The drawing is fully dimensioned and shows all identified variables that can be represented in a scale drawing. Although CAD resources are available, we feel that hand drawing on paper helps students see a better representation of their idea. The drawing then becomes a template for the blade and a construction guide for the turbine.

The last set of skills, experimentation and testing, are the major component of the turbine project. The students build and test their designs focusing on the variable/s that have the biggest impact on the output power of the turbine. We emphasize careful measuring, control of variables, and making notes about what is happening to their design as well as what they see in other designs. Since we test at one station, the students observe their peers while waiting their turn to test. This wait time often results in student-initiated discussions about the project similar to those taking place in an engineering conference room. Successes and failures are noted, and students incorporate their observations of the other designs into their next iteration. We supply a Turbine Test Data sheet where students note the test results, observations, and the different variables being evaluated.

In testing we use high quality equipment to mimic the look and feel of a real engineering lab. For example, in Figure 2 the students are measuring and setting blade angle with a digital protractor**.**

Figure 2. demonstrates students measuring the blade angle with a digital protractor. The information is used in the redesign process to improve turbine output.

The turbine design focuses on the output power so time is spent talking about basic electricity and power measurements, as this is essential knowledge about the project. When we start testing, the students measure voltage and current with digital voltmeters, and perform a manual calculation of the output power. On day three of testing, we use a LabView instrument that performs the power calculation and displays the results on an analog scale with color-coding. The analog scale and color code allows students to "follow the needle" on the instrument which corresponds to improved designs and additional enthusiasm for the project.

Assessment of student work in engineering

Current research on project-based learning points out the unique nature of assessment since, in many cases, the goal of the learning is process and skill development rather than the final outcome and judging creativity. Assessment in K-12 engineering "requires more than an evaluation of the end product" [26]; it requires embedded assessment through the use of informal questioning [27]; and the use of a portfolio [28] to assess the entire learning process. Even at the college level, assessment of design ability is difficult even though it is at the core of engineering competency [29]. In addition to design ability, assessment of other essential engineering skills, such as the ability to work in teams, understanding the impact of a solution on society, and communication of results, have led many to believe that a portfolio approach to engineering assessment is required. One benefit of a portfolio assessment in project- or design-based learning is the recognition of different styles of learning and the subsequent success of lower-achieving students. Studies have shown that lower-achieving students can out-perform their peers in a design-based learning environment that recognizes their learning style and evaluates their work in a non-standard, holistic manner [7, 30, 31].

In our curriculum, we utilize the portfolio-driven, holistic approach to assessment. This approach to evaluating student learning is consistent with our classroom environment where we have explicitly told the students that there is not one correct answer to the project, and that they will be evaluated on their thought process rather than the numerical result of their efforts. The project worksheets encourage the development of the thought process with final outcomes used as reference points rather than evaluative quantities. We also have to recognize the progress of non-traditional students even if they do not fully report their work in the project worksheets. During the test and redesign part of the project, we have numerous opportunities to listen to students and engage in one-on-one and small group discussions. This affords us the opportunity to assess students who have difficulty reporting their thoughts and ideas on paper. Doppelt et al. observed that “when the freedom to learn is given to low achievers, they might adjust their learning process and could be more creative” and that “assessment should capture their creative outcomes” [7]. These observations are consistent with our own classroom observations.

Since we are also trying to encourage all students to see engineering and STEM in a positive light, assessment has to encourage our core ideas of creativity, risk taking, not being afraid to fail, and the understanding of engineering skills and concepts. Our goal is to assess learning but also to show our students that they can “do” and hopefully enjoy engineering. As an exploratory course designed to open doors for all students, we use a holistic approach to student assessment rather than a formal rubric on the projects. At the middle school level the holistic approach to assessment aligns more closely with our ultimate goal of developing our student’s interest in engineering.

The Turbine Design Project

The Wind Turbine design project takes 10–12 class periods of 45 minutes. The project is a team-based design challenge where pairs of students attempt to design a turbine with the highest output power. The design activity focuses on the optimization of the turbine where students design and test blade geometry, materials, airfoil shape, number of blades, blade angle of attack, shaft length, and the mass of their turbine assembly. The goal of each team is identify the parameters with the greatest effect on the output power through experimentation and observation of other teams. Students strive to maximize the blade lift while minimizing energy consuming drag and mass.

In keeping with our theme, “Engineering: A Better World”, students learn about conventional and alternative energy sources, energy and electricity measurement, and how energy is used as an introduction to the 7th grade curriculum. Few students understand how energy is measured and how much energy people use in their daily lives. To help the students understand what it takes to light a 100-Watt light bulb, we have them ride an exercise bike attached to a car alternator so they can generate electricity to light the bulb. We call this 100-Watt (W) output a "kid unit" based on Wolfson's idea of an energy servant [32]. Few students are able to keep a 100W incandescent bulb lit for more than a minute. We then change to a 25W Compact Fluorescent Lamp (CFL) that provides the same amount of light as the incandescent bulb. Since the CFL bulb consumes 25% of the power of the incandescent bulb, most students can keep the CFL lit for a longer time. This exercise reinforces the concepts of power generation and consumption, measurement, and alternatives to traditional sources of energy. The "kid unit" of energy also provides a reference point that we can use to discuss the power requirements of the lights in the room, drink machines, televisions, and other energy consumers in the student's life.

The Wind Turbine project includes classroom discussion of commercial wind power. We offer the pros and cons of turbine technology and the impact on the environment. Since wind power is in the news, there is ample opportunity to bring current and relevant material into the classroom discussion. We also put wind power in context by linking the size and output of turbines to well-known landmarks and values from our town. For example, we pose such questions as:

> "A 7MW turbine will power approximately, 1,000 typical New England home. How many turbines would be required to support the 11,000 homes in our community?"
> "How many kid units are there in a 7MW turbine?"
> "Where would the turbines be located?"
> "Using wind maps for reference, does our town have sufficient wind to make using wind turbines cost-effective?"
> "How many turbines would be needed to support the school's electricity usage?"
> "What would happen to the school if the wind were not blowing?"

Since the idea of a "kid unit" has been introduced, students then calculate how many kids pedaling the bike would be needed to equal the output of the turbines to support the school and/or the town. With the kid unit reference to power, and the experience of the physical effort required to generate electricity, students are provided with a realistic representation of an abstract concept.

The student's turbines are tested in a standard, fan-generator test bed with a constant load on the generator to ensure that testing is conducted under consistent conditions (see Figures 3 and 4). This allows students to compare their test results to earlier results, and to the results achieved by their peers.

All team results from the prior day are posted on a whiteboard at the beginning of each class so students can see how their results and progress compares to the other teams (see Figure 5). As development and testing continues, we often find that a breakthrough result from one team inspires

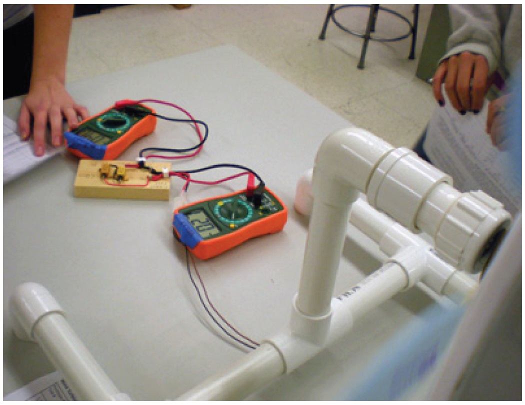


Figure 3. shows the test set up and digital voltmeters to measure voltage and current. Measurement of these variables is integral to student's evaluation of their design.

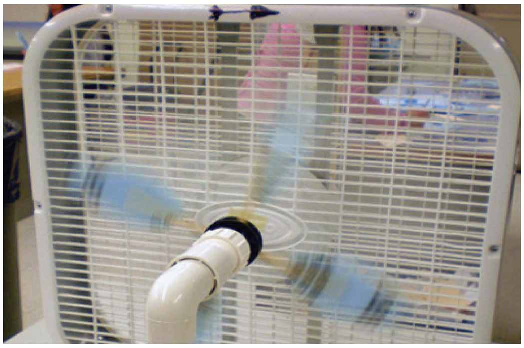


Figure 4. shows a turbine under a test.

subsequent thought and progress from other teams. A class will "catch fire" and turbine output power will often improve dramatically for almost all teams. Students are motivated to continue working on the project as their designs improve; scheduling usually allows us to add an extra day of testing if there is classroom consensus based on a classroom vote.

As mentioned previously, we ask students to think about the Universal Systems Model, (USM), as it relates to a wind turbine system. In our classroom discussion of commercial wind power, they see how a full-size turbine has internal sensing and feedback systems that optimize performance for various wind conditions. We link this back to their system where the student becomes the feedback and optimization system for the turbine based on their measurements and observations.

Project Development, Design Activity, Testing, and Reporting

All of our projects follow similar formats to provide general guidelines to help students learn and see how the engineering design process works. The Framework Lesson Plan is the starting point for our curriculum development after we have selected a design project for the students. We site the relevant parts of the state frameworks for the project and build our lesson plans and assessment sheets from the strands that we plan to cover. Note that in the Wind Turbine project, we address one of the seven strands in the Massachusetts framework. Over three years we find that we can cover most of the strands in the framework; however our emphasis in most projects is on strand two, which covers the EDP. For the design projects in our curriculum, we always start with a Design Brief and design drawings. The Test and Redesign sheet is provided for students to record measurements, variables and ideas for redesign. When the design and test phase is complete, we have the students report their findings in the Project Summary. Clicking the links will open pdf copies of the referenced worksheets that will be discussed in the next section.

In the Wind Turbine Design Brief, we introduce the project with a description of the need or problem: design a turbine that delivers the highest output power. We have a classroom discussion of the design constraints, materials, and measuring techniques required for the project. The Design Brief helps students focus their thoughts on the turbine design. It has the added effect showing engineering as a systematic process by explicitly stating the steps of the EDP covered in the brief. After a class discussion of the brief, student teams of two proceed with their design.

It is important to note that even though this is a team project, we ask students to complete their own Design Brief. We treat the first part of the Design Brief as the research and possible solutions steps of the EDP. Students have their own ideas about turbine design and this is an opportunity for them to put their ideas on paper before discussing them with their partner. It is interesting to see that despite their research, class discussions, and viewing of commercial turbines with 3 blades, students will invariably design turbines with 4 to 12 blades. Once each partner has completed their design, we encourage them to compare ideas and converge on a best possible solution through active discussion and resolution of differences. These conversations certainly mimic design group discussions that one would witness in a professional engineering environment.

Another reason for having students complete their own Design Brief (and Project Summary) is due to the dynamics of grouping, especially in the middle school environment. We want to encourage teamwork since it is such a vital part of engineering practice, yet we recognize that in the volatile social situations of middle school. Over time some pairings of students may not be optimal. By providing students with the opportunity to express their work individually, we can compensate for teams that may not work well together over the length of the project. We usually let the students pick their own partner for the project, however if we identify team issues we will address them as required.

When students finish their Design Brief and have selected a design, they are encouraged to sit with other teams and conduct a peer review. We foster a non-threatening and safe environment for students to express ideas; therefore we remind them to ask constructive questions rather than make judgmental comments. The goal is to have them look at what other teams have done and offer their constructive thoughts on their peers' designs.

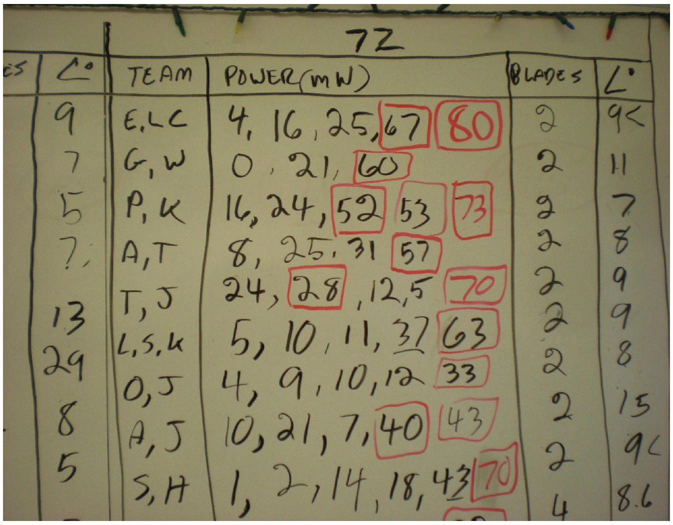
After the teams have completed the peer review and chosen their best solution, they make a scale drawing of one blade of their design. This scale drawing then serves as a template for cutting the actual blades used in the test. It is deliberate that we have the students make these drawings on paper to help them get the feel of scale and size, since the constraints of the project allow one blade to fit on a standard sheet of graph paper. We find this approach builds skills for the subsequent design project, Solar Powered Boats where we introduce orthographic projection.

When the students have completed their drawing they are given the materials to begin building their blades. Students construct the blades from 1/4″ blue foam insulation, dowels, and hot glue. Usually one or two groups will find and try a different material like Oaktag paper. To encourage interaction of the teams, actual testing does not begin until the next class session. We find that by removing the incentive to work fast so they can be the first group at test station, students engage in more discussion, and are more careful in their construction. Also, by working slowly the students are safer with the tools. At this point, due to the different work pace of the teams, there is the opportunity for the teacher to engage in a short dialog with the student teams about their design ideas.

On the Test Data Sheet students measure and record the following parameters of their designs: turbine radius, mass, number of blades, and blade angle and note any other parameters they are testing, such as twist, curvature, edge thickness. We do not tell students which parameter is the most important, but we do require them to only make one change at a time. Watching the activity closely and asking, “What happened?” and “What’s next?” during testing helps students understand the idea of systematic testing and refinement of their designs. We also make the distinction between prototypes and trials. A trial is changing a single variable on an existing design, for example, blade angle. A prototype is a new design where the team might change a 4-blade turbine to a 3-blade turbine using their existing set of blades. Inevitably, we have students who conduct one test and immediately request new materials to build new turbine blades. We gently redirect them to persist with their original design idea and continue testing. By the end of the first day most students have seen their turbine spin and have generated some power. On subsequent days, most teams can be seen following a systematic approach to testing with little intervention.

Our design and test classes always start with a group review of what happened during the previous class. Each team reports their output power, number of blades, and blade angle to achieve their best result from the prior day. Students share ideas and make comments since this time is structured as a group design review. Figure 5 shows the recorded results at the conclusion of five days of testing. The numbers show the daily progress of each team’s output power with their highest output power highlighted in red. It is important to note the improvement of each team’s results over the test and redesign phase of the project. As the days of testing proceed, the students seek new materials as they develop new ideas. We control materials and seek an explanation of their thoughts before they are permitted to use additional material.

Students are not required to construct a new scale drawing; however a sketch of the idea is part of the review process when they request additional materials. Some students grumble about this requirement, especially if they are asked to try another idea with the materials they already have.



72

∠°	TEAM	POWER(mW)	BLADES	∠°
9	E,LC	4, 16, 25, 67 80	2	9<
7	G,W	0, 21, 60	2	11
5	P,K	16, 24, 52 53 73	2	7
7	A,T	8, 25, 31 57	2	8
	T,J	24, 28, 12, 5 70	2	9
13	L,S,K	5, 10, 11, 37 63	2	9
29	O,J	4, 9, 10, 12 33	2	8
8	A,J	10, 21, 7, 40 43	2	15
5	S,H	1, 2, 14, 18, 43 70	2	9<
			4	8.6

Figure 5. shows test results after five days of turbine engineering. Final output power is noted by the value in a red square. Test results are posted so all design teams can concurrently use the information as they evaluate and redesign their turbine blades.

We find that this small push back helps them develop their thoughts more fully and, in many cases, look at their existing ideas differently. For example, a team may have a turbine with six blades. Instead of giving them new material to redesign the turbine, we ask them to think about what we have discussed and what results they see from other teams. They usually get the idea of trying a 4-blade or 3-blade turbine using their existing blade design on their own.

Our experience has shown that spiraling successive rounds of theory and practice results in better learning, more engagement, and better design outcomes. For example, before students start their Design Briefs, we discuss the forces that make a turbine move (lift) and those that slow it down by consuming energy (drag, and rotating mass). Within the discussion of lift, we talk about angle of attack lift (simple but inefficient), and the more efficient Bernouilli and Coanda effect forms of aerodynamic lift. Students begin to see how the various forms of lift can be combined but they are not able to apply this in practice until a number of trials have been conducted. As they proceed through the testing phase, we reiterate and probe more deeply into these theoretical concepts, asking students how they can use these ideas to design and implement improvements on their turbines.

Although we lead the active classroom discussion at the beginning of the project, the design and testing days are almost exclusively student-centered. Other than starting the discussion at the beginning of class about the previous day's results, our role during the test phase changes to that of an observer and counselor. Our main task is providing materials and checking-in with teams who are not as actively engaged, while encouraging all students to be responsible for their own learning. One of the most gratifying parts of this stage of the project is observing the students' development of ideas while learning from each other. As the results get better, the motivation of the students becomes higher. Although we do not reward the results of the design performance in final assessment, we find that students do enjoy the competition of trying to surpass their prior results and the challenge of having the highest output power in the class. The subtle competition drives the dynamics of the test days. By the end of testing most teams have shown significant improvement in their turbine's output.

Since testing and redesigning is such an important part of the project, we provide equipment that provides accurate measurements and requires thought and skill to understand what the measurements mean regarding their design. We start the test phase of the project by measuring power with digital meters as seen in this video clip. Students use the Test Data Sheet to record the design parameters (number of blades, blade angle, turbine mass) and the resulting output voltage and current. Space is also provided to record output power that the students calculate at the conclusion of the trial. Although measurement of electricity is not an explicit part of the framework, we include measuring with meters to build knowledge that supports our underlying energy theme.

On the third day of testing we change our measuring technique to a PC-based system with Vernier probes (Figure 6) and a LabView virtual instrument (Figure 7) developed by the authors. The instrument provides digital and analog displays of voltage, current, and power. The analog meter for output power is color coded by power level to help students visualize the changing data. We find that the introduction of this measuring system corresponds to increased turbine performance. Rather than causal significance, we believe that the analog measuring is coincident to the improvement on student designs after two days of test and redesign. We believe that the analog instrumentation provides more meaningful feedback than just digits on a meter, especially since the objective measurement is calculated and displayed in two different ways. Not only do students get instant and relative feedback on their design changes, the students waiting to test their designs see what their peers' designs are doing. When the first student group yells out, "We hit the red", most students gather quickly to see what is happening.

The turbine project concludes with the Project Summary, which encompasses our philosophy of assessment in our engineering projects by asking the questions, "What happened?", "Why did it happen?", "What changes did you make and were they successful?" and "How would you do it differently the next time?"

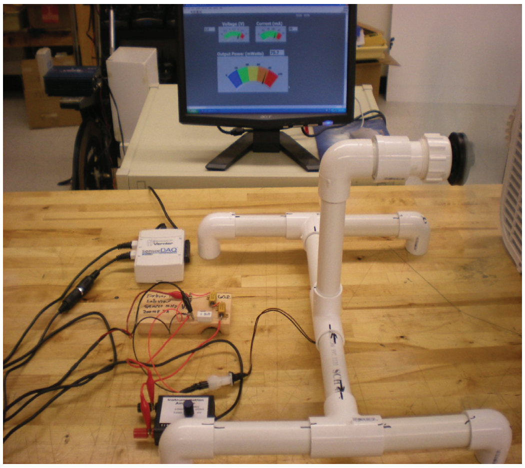
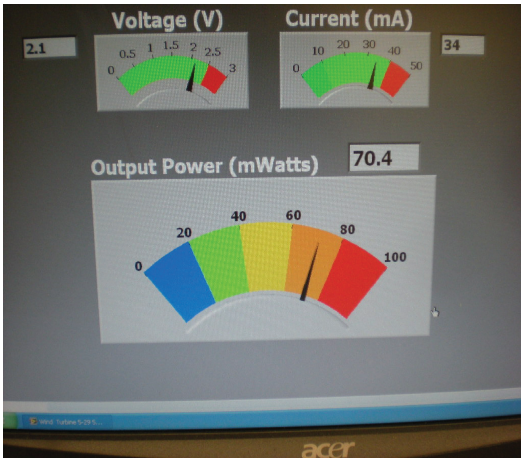


Figure 6. shows the test stand set up with Vernier instrumentation, (SDAQ, Voltage probe, and Instrumentation Amplifier).



Voltage (V) 2.1

Current (mA) 34

Output Power (mWatts) 70.4

Figure 7. shows the screen display from the LabView instrument. When a team "hits the red", students gather around the test station.

This assessment strategy focuses on the student's thought process over the entire project duration rather than the actual measured test results. When introducing the Project Summary, we compare and contrast examples of ways to answer the questions by asking students to think about the following: "I had the highest output power in the class because I'm a great designer" versus "I found that changing the blade angle had the most effect on my output power because...." Since we have embraced the questions of what, why, and how in the previous year, students focus on their thought process instead of the absolute results. Our students understand that there is not a single right answer and that almost any thought process is acceptable.

In the Project Summary we do ask the students to quantify the output and describe the design and the different variables of their best design. Students graph their results and interpret what their graph means. The EDP includes communicating results and we feel that graphing helps students express their ideas in a standardized way that has application in other subjects. By asking them to interpret their graph with a single sentence we gain insight to their thought process.

Qualitatively, we ask students to summarize the steps that they followed, and to discuss what worked best and what did not work as expected. We include space for drawing and writing the answers to the questions in the Project Summary sheets. Some students can express their ideas in pictures better than words, so drawing is used as a method of differentiating the assessment. We end the summary with a question that asks students to describe what they would do if they were to start this project again. Through this process, which includes a comparison of their best design to their first design on the Design Brief, we get an accurate assessment on their thought process.

We have found that most students are able to express their thoughts in words and pictures, providing us with a good way to assess their learning. For other students, who may have difficulty with this more traditional form of assessment, we ask them to explain what they did as they ponder the Project Summary, and then show us what ideas they had by explaining their blade design. Adding these student explanations to our observations and discussions during testing ensures a holistic assessment that benefits not only the non-traditional learner, but also all students in the class.

Assessment of the Project and the Curriculum

Over the past three years almost 1,000 students have completed the Wind Turbine project in our classes. Research 1done by others [7, 13–15] has documented the success of students, including non-traditional students, in a project-based engineering design curriculum. We expect that our students would show similar results given similar quantitative assessments.

Quantitative MCAS test results from the MA Department of Elementary and Secondary Education for the 8th grade Technology & Engineering multiple-choice questions were accessed and subjected to statistical analysis. The data for each question includes the framework foundation for the question and the percentage of students in the selected population who answered the question correctly. The mean percent correct answers were calculated for an Andover middle school (AMS) with a dedicated engineering program, the state, and a demographically equivalent middle school that does not have a dedicated engineering program (see Figure 8). The yearly means of the exam were compared with a Student's t-test and alpha level of 0.05.

The data shows that in 2010, students in a dedicated engineering program (AMS) exceeded the state average (STA) by 14% ($p < 0.05$). When compared to the demographically equivalent school district (DES) without dedicated engineering education, there was a trend for AMS students to exceed their peers by 4%. Data for the two previous years were not significant ($p > 0.05$). The student populations over the three years studied were relatively stable and averaged 184, 110, and 72,737 for AMS, DES, and STA respectively.

It is important to note the limitations of the data available. Even though the population of students taking the test year to year is relatively stable, the number of multiple-choice Technology and Engineering questions varies. In 2008 and 2009, there were five multiple choice questions and two open response questions, while in 2010 there were 10 multiple choice questions and one open response question. The open responses were not included in this analysis. Additionally, the range of questions and the frameworks addressed in the MCAS test are not consistent year-to-year, so the applied statistics may be influenced by this inconsistency. Besides the difference in test material, the

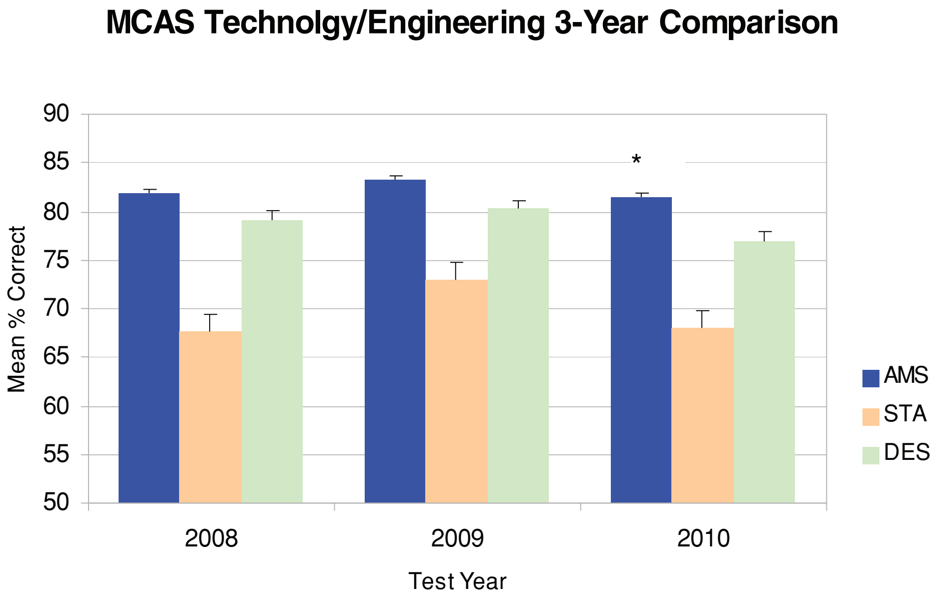


Figure 8. Comparison of yearly T/E MCAS scores of an Andover middle school with dedicated engineering (AMS), all 8th grade students in the state (STA), and a demographically equivalent middle school (DES). In 2010, the mean percent of correct answers for AMS exceeded the value of statewide scores (STA; $p < 0.05$). State scores compared to a demographically equivalent school district (DES) were not different ($p > 0.05$). Error bars show the standard error of the mean.

cohort of students tested each year is also different. The mix of students can vary in cognitive ability and motivation, compounding the limitations of a year-to-year comparison of the results. Further quantitative studies using MCAS or other standardized testing may elucidate the influence of these limitations on MCAS performance. Due to the presentation and reporting of the publicly available data from the Massachusetts DESE, demographic analysis of the results on the Engineering portion of the 8th Grade Science/Technology & Engineering MCAS could not be performed.

The insignificant difference between standardized test results between schools with and without dedicated engineering programs may lead some to question the validity of such a program. The MCAS data fails to capture the immeasurable, qualitative benefits that we have discussed in terms of the skills and thought processes learned by all students in an engineering classroom. Standardized testing does not necessarily reflect the abilities and achievement of our lower achieving and non-traditional students who generally do not perform well on standardized tests.

We can also report the anecdotal evidence of student success that we have observed in our years of teaching. Students come to class energized and engaged, and usually do not want to stop testing their design ideas when the class ends. Former students return to school to tell us how much they miss engineering class. We have also had outside observers visit our classrooms during the Turbine Project. One observer sent an email with thoughts of what she saw: “What a treat it was to see your students so engaged in such a fun learning project. The wind turbine project is indeed intriguing and I found myself getting “hooked” on wanting to build one too!” Formal and informal observations by our administrators confirm that our curriculum works well for middle school students. We have trained over 20 teachers on the turbine project who have implemented it in their science classes to give students a relevant engineering design experience.

CONCLUSION AND FUTURE WORK

We have presented a proven engineering design project that can be part of a stand-alone engineering curriculum, or that can be adapted to fit into a science curriculum where teachers want to provide a relevant design project. The project is well documented, is successful with middle school students, and can be implemented for minimal initial and yearly recurring costs. We have found that middle school students of all abilities can “do” engineering, and can learn the basics skills and concepts of engineering.

Engineering is important for middle school students as they are at a critical phase of deciding who and what they want to become. Reaching students at this point in their lives will not only help increase the interest in STEM education, but will also provide non-STEM students important, life-long skills such as the ability to successfully address open ended problems and the ability to see failure as a learning opportunity. Engineering is rooted in socio-constructivism and fits the unique learning needs of middle school students who thrive in environments where they can engage in social activities.

Like any engineering project, curriculum development and analysis of the results are never complete. The curriculum can always be improved, especially with new insights from the students. One way to assess the project and to provide additional qualitative analysis, will be coding student answers when we evaluate the Project Summary. Since we see 180–200 students annually, at all levels and abilities, we may be able to correlate certain responses to assess learning over large populations. Since the MCAS is a non-biased, standardized test administered to all 8th grade students, further analysis of MCAS data may help us identify areas where students are lacking important concepts, especially if we can obtain performance data on based on demographic performance on the engineering questions.

Finally, an effort should be made to follow-up implementation of the turbine project in the districts where there are teachers trained in our curriculum. Most of these districts have added the project to their Science curriculum; therefore looking at student work and evaluating student perceptions of engineering and their learning through clinical interviewing may also be appropriate for further assessment of the project and the curriculum.

ACKNOWLEDGEMENTS

We thank all of the students we have taught over the past several years. Their comments and feedback on the projects and the curriculum has been essential to our efforts to "engineer" the curriculum to the point where it is today. It is still a work in progress as we continue to learn every day from our students.

We also acknowledge Dr. Claudia Bach, Superintendent of Andover Public Schools, for her vision of making engineering a stand-alone subject in middle school, and for the freedom she gave a couple of ex-engineers to teach engineering. We thank our building Principals, The Andover Coalition for Education (ACE), The Andona Society, and the Andover Fund for Education for their support.

Also thanks to Dr. Maria Burgess for her editing and assistance with the statistical analysis.

REFERENCES

1. Massachusetts DESE, "Massachusetts Science and Technology/Engineering Curriculum Framework", pp. 81-99, (Malden, MA: Massachusetts DESE, October, 2006).

2. Richards, L., Hallock, A., Schnittka, C., "Getting Them Early: Teaching Engineering Design in Middle Schools", *International Journal of Engineering Education,* Vol. 23, No. 5, 2007, pp. 874–883.

3. Rivoli, G., Ralston, P., "Elementary and Middle School Engineering Outreach: Building a STEM Pipeline", ASEE Southeast Section Conference, Marietta, GA, April 5–7, 2009.

4. Hynes, M., Dos Santos, A., "Effective Teacher Professional Development: Middle-School Engineering Content", *International Journal of Engineering Education,* Vol. 23, No. 1, 2007, 24–29.

5. Reynolds B., Mehalik, M., Lovell, M., Schunn, C., "Increasing Student Awareness of, and Interest in Engineering as a Career Option through Design-Based Learning", *International Journal of Engineering Education*, Vol. 25, No. 4, 2009, pp. 788–798.

6. California Department of Education, "Characteristics of Middle Grade Students", Caught in the Middle, pp 144–148, (Sacremento, CA: California Department of Education 1989).

7. Doppelt, Y., Mehalik, M., Schunn, C., Silk, E., Krysinski, D., "Engagement and Achievement: A Case Study of Design-Based Learning in a Science Context", *Journal of Technology Education,* 19(2), 2008, pp. 22–39.

8. Staver, J., "Constructivism: Sound Theory for Explicating the Practice of Science and Science Teaching", *Journal of Research in Science Teaching*, Vol. 35, No. 5, 1998, pp. 501–520.

9. Rotjer, J., "PBL and Constructivism in Engineering Education", Proceedings of the 37th Annual SEFI Conference, Delft Rotterdam, July 1–4, 2009.

10. Vygotsky, L. S. (1978). *Mind in Society* (Cambridge, MA: Harvard University Press 1978).

11. Cheville, A., "Transformative Experiences: Scaffolding Design Learning through the Vygotsky Cycle", *International Journal of Engineering Education,* Vol. 26, No. 4, 2010, pp. 760–770.

12. Prince, M., Felder, R., "Inductive teaching and Learning Methods: Definitions, Comparisons, and Research Bases", *Journal of Engineering Education*, 95(2), 2006, pp. 123–138.

13. Kolodner, J., Camp, P., Crismond, D., Fasse, B., Gray, J., Holbrook, J., Puntambekar, S., Ryan, M., "Problem-Based Learning Meets Case-Based Reasoning in the Middle School Classroom: Putting Learning by Design™ Into Practice", *The Journal of the Learning Sciences,* Vol 2(4), 2003, pp. 495–547.

14. Kolodner, J., "Facilitating the Learning of Design Practices: Lessons Learned from an Inquiry into Science Education", *Journal of Industrial Teacher Education,* Vol. 39, No. 3, 2002.

15. Prince, M., "Does Active Learning Work? A Review of the Research", *Journal of Engineering Education,* 93(3), 2004, 223–231.

16. Cunningham, C., Knight, M., Carlsen, W., Kelly, G., "Integrating Engineering in Middle and High School Classrooms", *International Journal of Engineering Education,* Vol. 23, No.1, 2007, pp. 3–8.

17. Kimmel, H. Carpinelli, J. Rockland, R., "Bringing Engineering into K-12 Schools: A problem Looking for Solutions?", International Conference on Engineering Education -ICEE, Coimbra, Portugal, September 3–7, 2007.

18. Lewis, T., "Engineering Education in Schools", *International Journal of Engineering Education,* Vol. 23, No. 5, 2007, pp. 843–852.

19. McCuen, R., Kucner, L., "Introducing Engineering into American Secondary Education", *Journal of Science Education and Technology,* Vol. 2, No. 2, 1993, pp. 397–406.

20. Brophy, S., Klein, S. Portsmore, M., Rogers, C., "Advancing Engineering Education in P-12 Classrooms", *Journal of Engineering Education,* 97(3), 2008, pp. 369–387.

21. Sherman, T. Sanders, M. Kwon, H., "Teaching middle school Technology Education: a review of recent practices", *International Journal of Design Education,* 20, 2010, pp. 367–379.

22. Sohn, S.Y., Ju, Y.H., "Perceptions of Engineering Among Korean Youth", *International Journal of Engineering Education,* Vol. 26, No. 1, 2010, pp. 205–217.

23. Marshall, D., Summers, M., Woolnough, B., "Student's Conceptions of Learning in an Engineering Context", *Higher Education Research and Development*. Vol. 38, 1999, pp. 291–309.

24. Katehi, L., "Teaching and Learning Core Engineering and Learning Concepts in Grades K-12" in Engineering in K-12 Education, Understanding the Status and Improving the Prospects, Edited by Linda Katehi, Greg Pearson, and Michael Feder, pp. 119–147. (Washington, D.C.: The National Academies Press, 2009).

25. Silk, E., Schunn, C., "Core Concepts in Engineering as a Basis for Understanding and Improving K-12 Engineering Education in the United States. Paper presented at the National Academy of Engineering/National Research Council Workshop on K-12 Engineering Education, Washington, D.C., 2008.

26. Niekerk, E., Ankiewicz, P. de Swardt, E., "A process-based assessment framework for technology education: a case study", *International Journal of Technology and Design Education*, 20, 2010, pp. 191–215.

27. Poole, S., deGrazia, J., Sullivan, J., "Assessing K-12 Pre-Engineering Outreach Programs", 29th ASEE/IEEE Frontiers in Education Conference, San Juan Puerto Rico, November 10–13, 1999.

28. Doppelt, Y., "Assessing creative thinking in design-based learning", *International Journal of Technology and Design Education*, 19, 2009, pp. 55–65.

29. Davis, D., Gentili, K., Trevisan, M., Clakins, D., "Engineering Design Assessment Process and Scoreing Scales for Program Improvement and Accountability", *Journal of Engineering Education,* 2002, pp. 211–221.

30. Doppelt, Y., "Implementation and Assessment of Project-Based Learning in a Flexible Environment, *International Journal of Technology and Design Education,* 13, 2003, pp. 255–272.

31. Cantrell, P., Pekcan, G., Itani, A., Velasquez-Bryant, N., "The Effects of Engineering Modules on Student Learning in Middle School Science Classroom", *Journal of Engineering Education,* Vol. 95, Issue 4, 2006, pp. 301–310.

32. Wolfson, R., *Energy Environment and Climate,* (New York: W.W. Norton, 2008) pp. 25–32.

AUTHORS

Steve Cogger teaches Physics and Engineering at Reading Memorial High School, Reading, MA. He earned a B.S. in Electrical Engineering from Cornell University, an M.B.A. from Rutgers University, and an M.S. MSTE (STEM) Education from Tufts University. Prior to teaching he worked in Engineering and Sales positions in the electronics industry with a brief detour as a factory certified BMW technician.

Dan Miley teaches Engineering at the West Middle School in Andover, MA. He earned a B.A. in Political Science and an M.S. in Electrical Engineering from Union College. Prior to teaching, he held Engineering, Marketing, and Strategic Alliance positions in the high-tech industry. He completed his educator training at Lesley University and holds Professional teaching licenses in Engineering, Science, and Mathematics.