feature article

engineering for all:

a middle school program to introduce students to engineering as a potential social good

EfA opens students' eyes to the role engineers play in addressing significant global and community-based issues and concerns, and instills the confidence that, with continued STEM study, students can make a difference in the world.

by
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Introduction

Due to the essential roles technology and engineering (T&E) play in addressing global and environmental challenges, support for PreK-12 T&E programs has rapidly increased (NAE, 2009). In addition to the workforce and economic imperatives, engineering can and should be appreciated as a contributor to sustainable development and transformative improvement in quality of life. The UN *Sustainable Development Goals* (UNSDG, 2015) and the NAE *Grand Challenges for Engineering* (NAE, 2008) are solid foundations upon which curricula that prompt learners to seek solutions to authentic human needs can be developed. School-based engineering meets the needs of "millennial students who are civic-minded, team-oriented, and want to make a difference" (Gleason, 2008). There is growing recognition that T&E

This is the first of two TET *articles about* Engineering for All (EfA)*, a $1.7M National Science Foundation-funded project (Grant # DRL-1316601) that introduces middle school students to engineering, not only as a career path, but as an endeavor with potential for doing social good. Hofstra University and ITEEA are leading the Project. This article focuses on the EfA conceptual design. The subsequent article will focus on classroom implementation.*

*EfA created, tested, and revised two six-week Technology and Engineering (T&E) curriculum units that challenge students to develop design solutions to two important societal challenges: food scarcity (*Vertical Farming: Fresh Food for Cities*) and water scarcity (*Water: The World in Crisis*). In the Food Unit, students design a virtual model for a hydroponic vertical farm; in the Water Unit, students design and build a multilevel filtering system to supply safe water to a family in Bangladesh. The Project involved 22 T&E teachers and 755 students from diverse ethnic and racial backgrounds and geographic locations nationwide who assessed feasibility of classroom implementation. Lead developers of* Next Generation Science Standards (NGSS) *and* Standards for Technological Literacy (STL) *served as EfA co-PIs, so curriculum units align well with these standards.*

EfA curriculum portrays engineering as a route to sustainability and social equity; revisits unifying engineering themes (design, systems, modeling, resources, and human values) in different contexts; enhances engineering thinking; and actively engages **all** *students, not just those predisposed to engineering careers, in authentic, integrated STEM learning. EfA opens students' eyes to the role engineers play in addressing significant global and community-based issues and concerns, and instills the confidence that, with continued STEM study, students can make a difference in the world.*

Now completed, tested, and revised, EfA curriculum units are hosted on ITEEA's online learning management system (BUZZ) and available at no cost to members of the ITEEA STEM Consortium. A video overview of the program is available at www.youtube.com/watch?v=OQkowF2g53Q.

experiences can be pedagogically valuable for all students—not only in providing an effective way to contextualize and reinforce STEM skills, but also in mobilizing engineering thinking as a way for young people to approach problems of all kinds (Brophy & Evanelou, 2007; Forlenza, 2010). Research indicates that student interest in STEM subjects begins to wane in middle school because of the lack of attention to the human-made world and the artificial separation of subjects (NGA, 2007).

Curriculum Development Process

Survey data obtained from STEM leaders (n=165) prior to the EfA Project informed the EfA design. Using a five-point Likert scale survey, it was found that STEM leaders believe that curriculum driven by broad themes (systems, design, modeling, resources, human values) would have high appeal to students (rated 4.43). Designing solutions to address social issues was rated even higher (4.58). The survey also found that design-based ETE curriculum would be very appealing to teachers (4.29) and to middle school students (4.16). However, respondents felt that teachers have little access to such materials (2.62) and use them rarely (2.58).

The four-year curriculum development and implementation process was designed to address the concerns identified in the survey. It involved several stages of iterative design, testing, and revision. Advisory board reviews, suggestions from participating teachers, and research and evaluation data contributed enormously to curricular improvements.

EfA curriculum team leaders led the development of the Units. Barry Burke (ITEEA), and Dr. Sandra Cavanaugh (Canon McMillan HS, PA) led the Water Unit development. Mariel Milano (Orange County Schools, FL), and Dr. Cary Sneider (Portland State University, OR) led the Food Unit development. Team leaders were in constant communication to ensure that the two units reflected consistent format and pedagogy. The team leaders worked closely with Project leadership and expert T&E teachers (below) to draft, classroom-test, and revise the materials.

Product Produced

EfA produced exemplary materials for students, two teachers' guides, assessment tasks and rubrics, research about design pedagogy, and external evaluation results.

Food Unit Teachers	**Water Unit Teachers**
Cimorelli, Nick (NY)	Banks, Dr. Carolyn (NC)
Cogger, Jake (OR)	Booth, Blaire (GA)
DeHaan, Christopher (MI)	Cavanagh, Dr. Sandra (PA)
Donlon, Jeff (NY)	Longware, Alta-Jo (NY)
Evans, Charles (MD)	MacDonald, Steve (NC)
Haner, Stephen (OR)	Melton-Koch, Jean (MD)
McGuire, Matthew (NY)	Meyer, Charles (NY)
Porter, Chandra (GA)	Ng, James (NY)
Shoemaker, Korbin (MD)	Plummer, Matthew (PA)
Storella-Mullin, John (MA)	Tedeschi, Michael (MD)
Wood, Stewart (OK)	Zalno, Jason (PA)

Figure 1. Middle School Student Hydroponic System Designs. *Courtesy of Korbin Shoemaker.*

Exemplary Materials for Middle School Teachers and Students

EfA developed two middle school curriculum unit exemplars relating to food and water scarcity that revisit T&E unifying themes (design, modeling, systems, resources, and human values) in authentic and important social contexts (Figure 1). Student learning activities provided students with the knowledge they would need to engage in designing solutions to the food and water design challenges; teacher materials were developed to provide clear and pedagogically driven instructional support.

The format for the EfA units parallels other Engineering byDesign™ (EbD™) Units developed by ITEEA and includes components related to (A) the first four days of instruction; (B) knowledge and skill builders; and (C) a Grand Design Challenge.

A. The First Four Days

The First Four Days are designed to accomplish three learning goals:

1. Position design-based activities and the informed design process as essential components of the classroom's daily routine.

Table 1: The Food Unit—Vertical Farming: Fresh Food for Cities

Food KSB Title	Food KSB Description
KSB 1: Welcome to Fresh Food Engineers	Students are informed that they have been hired to work in an engineering company that specializes in hydroponic systems design and will be asked to design a large vertical farm. First, they need to learn about hydroponics and CAD. The KSB introduces students to the need to feed a rapidly growing population, the pros and cons of hydroponics for growing food, and describes four different hydroponic systems.
KSB 2: Design and Build a Platform	Students learn to engineer a product. They are shown the materials that they will use (either wood or PVC tubes). They are given the challenge of designing a platform that will hold the growing chamber and reservoir, allow for tubes to pass between them, and hold lights that can be adjusted. The teacher guides the students in designing their platform, creating a bill of materials, making tradeoffs, and using a design matrix. Students build their platforms.
KSB 3: Engineer a Hydroponics System	Students work in teams to design and build **aeroponic** systems in which the plant roots are suspended in a chamber, which is constantly misted with nutrient-rich solution, and an **ebb-and-flow** system in which the plants are placed in cubes of an absorbent material.
KSB 4: Hydroponic Farming	Students mix the nutrient solution, place seedlings in their hydroponic systems, and set timers. They monitor their hydroponic systems two or three times a week and record data, such as plant height, color, and number of leaves, as well as quality of the water and temperature and humidity of the air. Finally, they graph the data and harvest the food.
KSB 5: Modeling With Computer Aided Design	Students learn to use CAD software on a simple project, to develop their skills in preparation for the Grand Design Challenge later in the unit. Students create a 3D model of an apartment building, which they will later use to demonstrate their solution to the Grand Design Challenge (virtually modeling a vertical farm).

2. Introduce students to the instructional format of the unit's predesign tasks known as Knowledge and Skill Builders (KSB). Students will learn to use KSBs to inform their understanding of content before engaging in design challenges.
3. Measure students' prior knowledge on unit material through the use of a pretest.

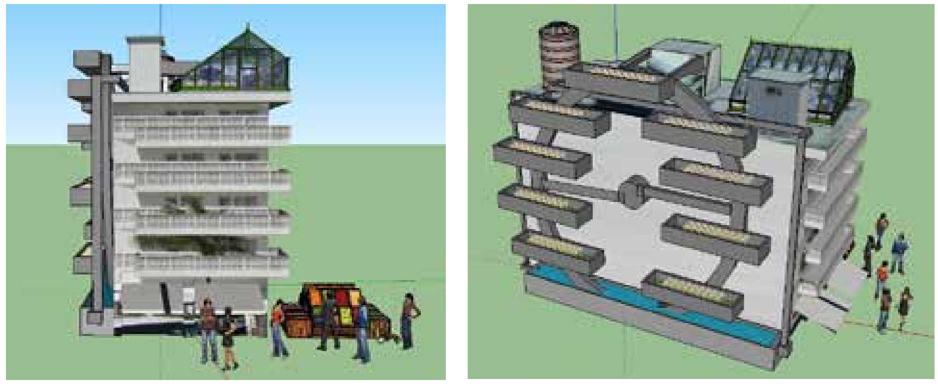

Figure 2. Student-designed Hydroponic Vertical Farming Systems. *Courtesy of Stephen Haner.*

During this time period, students do a short activity to "Build the Tallest Tower" without instruction. They then redesign their towers and learn to design a more stable structure, guided by informed design pedagogy (Burghardt & Hacker, 2004) where students do inquiry-based tasks that build knowledge and skill before they begin designing. The pedagogy was developed and validated in prior NSF projects led by the Hofstra Center for STEM Research (CSR) (Flugman & Hecht, 2008; Hofstra University, 2004, 2008). In informed design, students are presented with short, focused, just-in-time predesign tasks called Knowledge and Skill Builders (KSBs) that enable them to gain the knowledge needed to approach a design challenge from an informed perspective (rather than by trial-and-error gadgeteering).

B. Knowledge and Skill Builders

(approximately four weeks of instructional time)

Before students begin working on the unit's design challenge, they engage in KSBs in both Units (Tables 1 and 2).

C. Grand Design Challenge

(approximately one week of instructional time)

Both units culminate with a capstone Grand Design Challenge (GDC) where students apply knowledge gained through KSBs to the solution of a design problem. The Food Unit GDC is to design a model of a vertical farming system using Google SketchUp or another CAD program. The Water Unit GDC is to build a multilevel filtering system to supply safe water to a family in Bangladesh based on in-class student investigations (see Figures 1, 2, and 3 for Food and Water images).

Revisiting Unifying Themes in Context

Both Units revisit unifying T&E themes (big ideas) in context. The themes are those repeatedly referenced in the T&E literature (Custer, Daugherty & Meyer, 2009; Rossouw, Hacker & de Vries, 2010; Hacker & Barak, 2017) and include design, modeling, systems, resources, and human values. Several examples are shown in Table 3 to illustrate how thematic ideas are addressed within the units.

EfA Assessment and Research Program

Development of EfA assessments was led by Dr. Michal Lomask, a nationally known assessment expert. Project research was led by Dr. David Crismond, whose research interests and expertise relate to informed design thinking and learning in students and the development of design pedagogy in teachers. The assessment and research components were related and intertwined; thus, Lomask and Crismond worked as a team throughout the Project.

Table 2: The Water Unit—Water: The World in Crisis

Water KSB Title	Water KSB Description
KSB 1: Water is Life	When students finish KSB 1, they will be able to answer the following questions: (1) What is water scarcity? (2) What areas of the world are affected by water scarcity? (3) What is the difference between the two types of water scarcity? (4) What are the impacts of water scarcity on life?
KSB 2: Turbidity Matters	KSB 2 addresses the following questions: (1) What is turbidity? (2) What makes water turbid? (3) What are the effects of turbidity? (4) How can turbidity be measured? (5) How can a device that measures turbidity be constructed?
KSB 3: Heavy Metals!	In this KSB, students learn about physical, chemical, and biological water contaminants, how they enter water sources, and the kinds of impacts each may have on human health.
KSB 4: Clean Up Your Act!	Students learn that in many parts of the world, people may not have a water treatment facility or nearby water well. In many places, even if there is water nearby, it is contaminated and can be a source of deadly diseases. Students learn to detect and remediate physical, chemical, and biological contaminates in water and illustrate a water filtration system in a systems diagram.


Figure 3. Water Unit Students Designing Filtering Systems. *Courtesy of Sandra Cavanaugh.*

Assessment Development

Assessments were developed and used to determine how well students mastered important EfA ideas. Constructed-response and selected-response assessment items were developed, tested, and embedded within the Units. The Grand Design Challenge served as a performance assessment, and a rubric was developed to assess student design work (see Appendix I in online version of article at www.iteea.org/Publications/Journals/TET/TETNov2017/121424.aspx#publicationContent). Assessments are shown in Table 4.

Design Teaching Portfolios. A framework for developing design teaching portfolios was developed to include teachers' written logs and reflections, teacher-annotated student work, and three 5- to 10-minute teaching videos. Portfolios were reviewed by the research and assessment team to gather data about curriculum implementation and common instructional practices of participating teachers. The portfolios also provided ongoing feedback to curriculum developers. Copies of student work and classroom videos from submitted portfolios became part of the training materials for teachers new to the Project (for example at ITEEA international conferences). Analysis of teacher portfolios by the research team indicated that EfA teachers were confident in knowledge of design practices and in supporting students to work in teams, but their grasp and depth of portrayal of concepts, especially science concepts, varied considerably.

Research on Design Pedagogical Content Knowledge

A validated instrument was developed and tested to help scaffold and measure teachers' knowledge of engineering design pedagogy. This instrument includes a set of design teaching standards (DTS) (see Appendix II in online version of article at

Table 3. Revisiting Overarching Thematic Ideas in Both Contexts

Overarching Thematic Ideas	Food Unit	Water Unit
Systems have parts that work together to achieve desired results. Feedback involves monitoring and adjusting a system to maintain a desired output.	Design, build, and monitor a hydroponic system.	Learn about and analyze water treatment systems.
Use representational **modeling** to convey the essence of a design. Create and test a physical model to ensure that a design solution meets given criteria and constraints.	Use CAD to model a vertical farm.	Develop a model of a turbidity tube and generate data.
Resources include information, people, tools, materials, capital, energy, and time, all of which are needed in technological endeavors.	Identify and use resources to build hydroponic systems.	Identify and use water filtration system resources.
Human Values. The aim of engineering should be to benefit society and the environment.	Feed a rapidly growing population.	Eliminate drinking water contaminants.
Grand Design Challenge: Iteratively design and construct a model or full-scale product, system, process, or environment that meets given constraints and performance criteria.	**Food Unit Grand Design Challenge:** Design a virtual model for a vertical farm system informed by tests and KSB research.	**Water Unit Grand Design Challenge:** Design and build a multilevel filtering system to supply safe water to a family in Bangladesh.

www.iteea.org/Publications/Journals/TET/TETNov2017/121424.aspx#publicationContent) and accompanying rubrics organized around three key dimensions of teacher knowledge needed to support students in doing informed design with engineering tasks.

The first dimension of the DTS is the **knowledge of design practices** (design process skills used in context). These include framing the challenge, doing research, generating alternatives, making decisions, prototyping, testing, iterating and improving, and communicating and reflecting.

The second dimension relates to **cross-cutting engineering themes**. The DTS addresses EfA overarching themes (design, modeling, systems, resources, and human values) that are of particular concern when supporting informed design thinking and that apply to a wide range of engineering challenges.

The third dimension of teacher knowledge relates to **classroom instructional practices**. Like engineers and designers, teachers using design tasks need to have relevant STEM content knowledge. This dimension addresses the specific pedagogical content knowledge (PCK) that teachers need to know to teach curriculum-specific concepts and to be able to support students in engaging in the design process; it also includes general teaching knowledge (e.g., planning and adapting lesson plans). The DTS were developed to describe this design PCK (Crismond and Adams, 2012). The DTS were developed and validated through surveys of experts in design, teachers of technology and engineering, and researchers in engineering education and the learning science. The research team also used approaches found in Design-Based Research (DBRC, 2003) where the work of teachers, curriculum developers, and educational researchers gets blended together.

Evaluation Results

As part of the development process, EfA undertook an evaluation of the curriculum specifically focused on the feasibility of curriculum implementation in middle school technology classes. Dr. Deborah Hecht, Director of the Center for Advanced Study in Education at the CUNY Graduate School led the external evaluation. Data came from reviews of the materials and feedback from students and faculty who used the curriculum. The evaluation examined several areas related to classroom feasibility, as described below.

Feasibility related to schedule and time. The first-time teachers ran out of time and were unable to complete the unit. By the second implementation, teachers typically reported that they were able to make adjustments and complete the full unit within the time available. The structure of the materials provides opportunities to deliver the content in different ways depending upon the available time (e.g., combining both units into a half-year course).

Feasibility of being able to use EfA within given school facilities. Delivery of EfA requires physical facilities and equipment. Both units require space to store student materials and work, raising challenges for teachers who wanted to offer EfA in multiple classes. Generally, teachers found ways to overcome these obstacles.

Resources and budget feasibility. Interviews with teachers revealed they had widely different available budgets for purchasing the types of supplies needed for EfA. Teachers with limited budgets brainstormed solutions such as reusing and recycling materials or substituting different materials, expressing confidence they would be able to gain access to what was needed.

Table 4. Summary of the Assessment System in the EfA Units

Assessment Goal	Assessment Tasks	Administration
Quick evaluation of students' learning of main **content** during each KSB.	▪ Selected-response (SR) items ▪ Short constructed-response items	▪ The quiz is administered by the teacher at the end of each KSB in the unit.
Engagement in learning and monitoring students' progress and understanding of **concepts** and **processes**.	KSB-based small performance tasks, such as: ▪ Written explanations ▪ Labeled drawings ▪ Concept maps ▪ Posters ▪ Short scientific experiments	▪ The learning activities are performed by the students during each KSB. Student work is gathered and evaluated by the teacher, using standardized task-specific performance rubrics.
Documenting students' work and achievement on the unit's main **design challenge**.	▪ Structured design challenge at the end of the unit	▪ Structured design journal is completed at the end of the unit and student work is evaluated by the teacher using standardized design-based performance rubrics.

Professional development feasibility. It was clear that professional development is important, but once trained, teachers could easily use the materials. The EfA team continues to expand the ways that teachers are trained and to improve the procedures they use. ITEEA is a partner in these efforts and is currently planning ways to promote the materials and offer professional development workshops.

Social context feasibility. EfA addresses social issues, and the social context dimension resonated with students. As one teacher noted, "I loved how this opened my students' eyes to a growing problem that is affecting other kids their age around the world." When asked if the social issues addressed by EfA would be meaningful to students, most responses were overwhelmingly "yes."

Instructional feasibility. An important topic was to understand whether it made sense to add EfA to the current T&E program. Teachers and administrators agreed about the importance of teaching about design and the unifying engineering themes. Many noted EfA was "different" from what they normally teach.

Availability of Materials

Now completed, tested, and revised, the EfA curriculum units are hosted on ITEEA's online learning management system (BUZZ). They are available gratis to members of the ITEEA STEM Consortium. Contact ITEEA for further information.

Summary

Because of its focus on engineering's potential as a social good, the use of important societal problems as instructional contexts, and the revisiting of overarching T&E themes, EfA represents a new paradigm for Technology and Engineering Education. This Project is the result of several years of development, classroom testing, and revision involving expert and experienced T&E teachers, university teacher educators, researchers, and advisors with deep pedagogical and technical expertise. It is our sincerest hope that our colleagues in STEM education will use and contribute to the further development of these materials and to the advancement of instruction that engenders a sense of social purpose in our students.

Acknowledgements

The authors would like to acknowledge the contributions made by several colleagues to the design, classroom testing, and dissemination of EfA materials. Anthony Gordon (Hofstra CSR) helped frame the curriculum, conceptually, through early drafts and developed lists of supplies and vendors. ITEEA leadership personnel Steven Barbato, Jennifer Buelin, and Anita Deck were especially helpful in arranging PD workshops and in disseminating results to the T&E community. Special thanks are due to Dr. Sandy Cavanagh, (PA), Christopher DeHaan (MI), Steven Haner (OR), Chris Malanga (NY), Matt McGuire (NY), and Matthew Plummer, (PA) for conducting EfA PD workshops.

References

The references associated with this article are available in the online version at www.iteea.org/Publications/Journals/TET/TET-Nov2017/121424.aspx#publicationContent.

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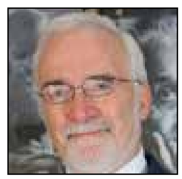

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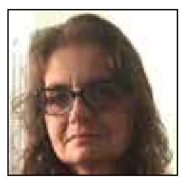

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