International Journal of Engineering Education Vol. 29, No. 1, pp. 154–169, 2013
Printed in Great Britain

0949-149X/91 $3.00+0.00

New Approach to Effective Teaching of STEM Courses in High Schools*

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Many educational teaching methodologies are designed from a specific pedagogical stance that relies on known teaching models like the T4E that promote active learning, learning intentions, lesson arrangement, and effective delivery of teaching style. In this paper we describe our study on "CAPstone, Unique Learning Experience (CAPSULE)" methodology that promotes engineering-based teaching and learning model at the high school level. The purpose of this study is to train teachers in using the new methodology and then observe their experience with the implementation in their classrooms. This study will contribute to our improved understanding of how high school students absorb STEM subject content. Data for the study were collected during the teachers' summer professional development workshops conducted in 2010 and 2011 using CAPSULE methodology. A total of 51 high school teachers participated in the study. During these workshops each teacher develops a unique strategy for his or her classroom aimed at creating a sustainable learning environment for students to learn and retain STEM principals. The engineering-based teaching and learning model emphasizes the engineering-design process and capstone experiences to relate the content of science to real-world applications. Our findings indicate that teachers' uninformed perception of engineering-based teaching influences their pedagogical practices. Our findings also indicate that CAPSULE methodology can positively affect STEM teachers' in-class pedagogical behavior and their classroom teaching. Lastly, our research has implied that the CAPSULE methodology can have an impact on students' ability to connect STEM concepts to real-world application resulting in better understanding of STEM in their environment.

Keywords: capstone experience; engineering-based teaching and learning; engineering-design process; research; design

1. Introduction

In spite of many local and national efforts to encourage high school students to enter science, technology, engineering, mathematics (STEM) collegiate careers, fewer and fewer high school students are applying to college to become engineers, mathematicians, or scientists. According to Bureau of Labor Statistics, the STEM/IT workforce is the fastest growing industry need in the United States. We believe that by improving K-12 instruction, the landscape of students entering STEM majors can be drastically altered.

It was estimated that 3.3 million high school diplomas were awarded for the 2010–2011 academic school year. In 2010, Raytheon, The Ohio State University, and the Business-Higher Education Forum released a report documenting the STEM pipeline. In 2001, 2.7 million students graduated from high school. Out of 1.7 million college freshman entering universities in the Fall of 2001, only 233 000 pursued and finished a collegiate career as a STEM graduate [2, 3]. If we extrapolate 3.3 million graduating high school students to the 4-year collegiate graduating class of 2015, there will only be 284 778 STEM graduates—a very small 20% increase in graduates. STEM interest and education begins at the K-12 level; and although all K-12 education needs to be addressed, the 11th and 12th grade high school students are the immediate concern to impact the workforce in 5–10 years.

There are many factors that contribute to the enrollment of high school students into college STEM programs and careers. However, the most evident appears to be the pre-college preparation and education about the career possibilities in STEM. The K-12 educational system has failed to prepare students adequately for careers in science, technology, engineering and mathematics. In a recent study from the *Journal of Research in Science Teaching*, the authors used the concept of identity—as students develop knowledge, competence and meaning from social interactions, they begin to form their own identity and perspectives on who they are and who they wish to be. In their study, researchers discovered from their sample population that no new strong interest in STEM career occurred *after* the 10th grade, indicating a direction away from SEM (science, engineering, medicine) careers. Of the 33 students they initially interviewed who held a strong interest in SEM careers during grade 10, 15 students no longer wished to pursue SEM careers by the 12th grade due to poor interactions and experiences, few science-related extracur-

* Accepted 19 September 2012.

ricular experiences, and no strong mentors pushing students toward SEM careers. Students today lack the understanding of how STEM theory plays a role in everyday lives. Without this understanding, students are at loss for information to make informed decisions regarding their college applications. We believe that students' understanding of STEM fields can be improved by relating STEM theory to reality at K12 level.

Responding to this need, we conducted a study through "CAPstone, Unique Learning Experience (CAPSULE)"program. It is an intensive two-week professional development course for high school STEM teachers and educators. CAPSULE program focuses on high school teachers to maintain students' interest in STEM subjects through high school grades. In this program, we employed engineering-based pedagogical techniques to teach participants 3D modeling techniques and the iterative engineering-design process to solve open-ended problems in their classroom. The motivation behind our research is that students are unable to connect the theoretical principles they learn in STEM courses with real-world applications; when students don't make this connection they lose interest in the abstract STEM subjects. CAPSULE program creates a bridge to connect STEM theory to real-world capstone projects. Ultimately, high school students need to understand that the theory they learn in their math and science courses is applicable to their life and not just an abstract theory. This process begins with high school educators.

We achieve this objective by observing STEM teachers' pedagogical techniques. In a professional development setting, we learn how teachers engage their students to transfer knowledge. Through our CAPSULE methodology, we examine teachers' reflections and experiences on the engineering-design process, 3-D CAD modeling, and capstone experiences, all of which provide the preeminent combination of tools to implement controlled hands-on, real-world problem solving in the high school classroom. The CAPSULE program brings the well-known university capstone design course and experience to high school teachers and students. A university capstone design course is the culmination of an undergraduate college experience. Capstone courses force students to apply the skills and theories learned in their undergraduate courses to a single open-ended problem. In many cases today, capstone projects produce patentable solutions to industry problems. Students work in design teams (typically four students), select a semester or year-long open-ended project, and present their project ideas to panels of judges. Once approved, student teams follow the engineering-design process steps to develop a series of solutions and determine the best-fit solution given the constraints. A team of students create a model of their final solution, develop a prototype and produce a final report, presentation, and poster.

2. Purpose (hypothesis)

The purpose of this study is to examine the impact of the engineering-design process and capstone experience in a high school classroom environment. Specifically, this study addresses the following research questions. 1) What is the influence of using the engineering-design process on high school students' ability to connect their conceptual understanding in STEM concepts to real-world application? 2) What are the students' and teachers' perception of the CAPSULE methodology and how does it change their learning and teaching outcomes? and 3) What effect does the CAPSULE methodology have on the course and lesson implementation for the upcoming academic year at participating high schools?

3. CAPSULE program

The CAPSULE program was developed in response to an NSF's effort to increase the number of K-12 students interested in STEM subjects and related technical disciplines nationwide. CAPSULE was funded by the NSF's Innovative Technology Experiences for Students and Teachers (ITEST) program to bring engineering-based learning to high school classrooms.

CAPSULE is an experience for high school teachers to engage in a college level-learning model. The fundamental purpose of CAPSULE is to captivate high school students effectively to entice them to pursue STEM education and eventually STEM careers. CAPSULE employs a top-down, engineering-based teaching and learning method. The top-down methodology was developed to increase the retention rate of material covered [7, 8]. This methodology encourages iterative learning and refinement on an "as-needed" basis. The key to this approach is that students take ownership and leadership of their own learning. However, this method is only successful if teachers know and understand how to implement it in their own classrooms.

Although the idea of exposing teachers to technical project-based learning (PBL) is not new, CAPSULE streamlines the process of solving complex technical, open-ended problems. PBL was first developed for medical education in the 1950s to address unsatisfactory performance in clinical environments, which emphasized memorization and theory. PBL has been studied and researched extensively in engineering education [10, 11]. The benefits of teamwork and lifelong learning are well documented with regard to PBL. Although PBL is non-traditional real-world problem solving, it does not offer systematic directions for relating theory to real-world applications. We refined PBL to create an engineering-based teaching and learning model by borrowing pedagogical models from engineering, including the engineering-design process and the capstone experience. For students, success is measured in multiple ways rather than the traditional one-problem-one-solution approach.

For engineering modeling and analysis, students typically use Solidworks™, a CAD/CAM 3D modeling system. When the final design is determined, students convert their 3D virtual models to a STL (stereolithography) file format type that allows prototyping machines to print their final models. The CAPSULE program demonstrates to participants (high school teachers) the step-by-step process for creating a product. This demonstration shows how engineers use virtual tools to change attributes such as material and evaluate how different materials change the physical properties of the product.

Massachusetts is one of the first states to mandate an engineering and technology curriculum into high school education. For CAPSULE, the engineering-design process was adopted from the Massachusetts State Framework. Massachusetts state standards are aligned with national standards determined by National Educational Technology Standards (NETS) and issued by International Society for Technology in Education (ISTE). We have also coordinated the CAPSULE curriculum with Standards for Technological Literacy (STL) issued by International Technology Education Association (ITEA) to allow for seamless scale-up of the program at the national level. The Massachusetts State Framework involves seven critical topics. (1) Engineering Design; (2) Construction Technologies; (3) Energy and Power Technologies—Fluid Systems; (4) Energy and Power Technologies—Thermal Systems; (5) Energy and Powers Technologies—Electrical Systems; (6) Communication Technologies—Electrical Wire, Optical Fiber, Air, and Space; and (7) Manufacturing Technologies. The CAPSULE curriculum has been aligned with the Massachusetts Framework, focusing on two specific topics. Engineering Design and Manufacturing Technologies [15, 16].

These two specific concentrations were selected because they leverage the core CAPSULE team expertise. Further, they have a direct and immediate correlation with everyday life for students. Students learn by doing—by analyzing and understanding topics and theories relevant to their world. CAPSULE was envisioned to connect theory and real-world capstone projects. There are three critical components to the CAPSULE methodology. (1) Engineering-Design Process; (2) Capstone Experience; and (3) Computer-Aided Design (CAD).

CAPSULE methodology begins with fully understanding the engineering-design process, which offers a consistent approach for teachers and students to follow. It also promotes iterative learning and constant improvement. The engineering-design process contains eight specific steps as shown in Fig. 1. The engineering-design process is a systematically organized chaos where every step has more than one solution and more than one method (i.e. a classroom of students is divided into groups of three or four students, each group has its own methods). CAPSULE emphasizes that there are many ways to solveing a problem. While each solution has its benefits and disadvantages, eventually the "design team" must determine how to take multiple solutions and narrow them down to a single solution as the final choice. By repetitively using the engineering-design process, it will eventually become an intuitive mindset for theoretical applications.

CAPSULE engrosses teachers in engineering-design process methodology and 3D modeling, which are the two primary tools used at university-level capstone projects. Additionally, CAPSULE provides resources, technology and experts at the teachers' disposal for implementation of capstone experiences in their classrooms. The first week of CAPSULE is used to cultivate technology skills and familiarize the teachers with the engineering-design process as a systematic way of thinking. Through this process, participants' perspectives begin to change. They begin to look at products in a different view, realizing that they now understand the general process of how *this product* was designed, manufactured, distributed, and sold through a step-by-step process. They begin to think about problems pertaining to the subject matter they teach. They explore solutions to problems rather than just accepting poor designs. The second week teachers take what they learned during Week 1 and apply it to their classroom content and create implementation plans. Week 2 is filled with educational partners that provide resources and tools for classrooms. Each day, CAPSULE builds upon the previous day, increasing proficiency as the week progresses; each Friday reserved as the "capstone presentation day" to provide teachers with the opportunity to speak on what they have learned and how they are going to implement it.

3.1 Participants

In year one, the program had twenty-three participants and twenty-eight participants in year two. Participants were selected based on their background and references. Many participants had pre-

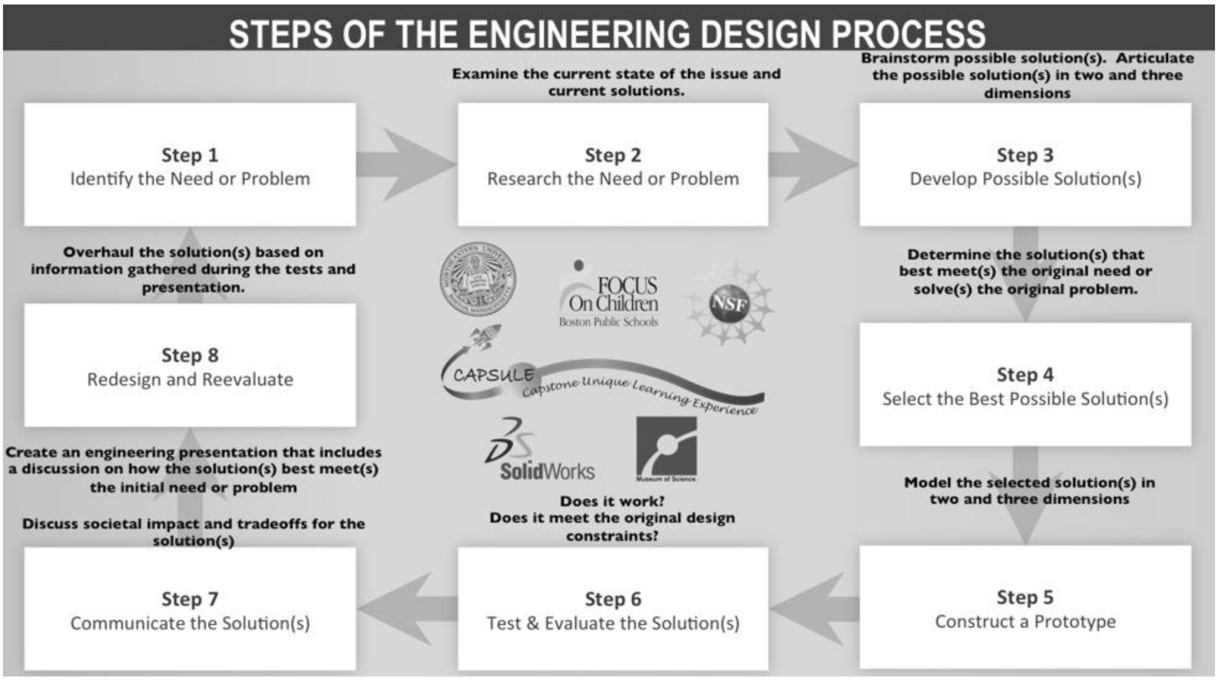

Fig. 1. Engineering-design process.

viously attended other research based curriculum programs such as Research Experiences for Teachers (RET) and Engineering the Future (ETF); it is a cohort of experienced teachers. Participants from year two included fifteen males and thirteen females. In this pool, 63% of participants were scheduled to teach high school juniors and seniors in the upcoming school year, while 37% taught freshman and sophomore level classes. From the program's perspective, the division of male and females was encouraging considering that engineering and STEM related fields were dominated by white males. The teachers from all grades were represented with the distribution of 15%, 22%, 31%, and 32% for grades 9, 10, 11, and 12 respectively. Year 1 participants had approximately a similar distribution.

Figure 2 provides the breakdown of courses taught by teachers for year two. Similar to the trend in Year 1 of CAPSULE, a large percentage of teachers were teaching physics (33%), and technology and engineering (29%). From Fig. 2 it is obvious that CAPSULE participants are well distributed across multiple STEM subjects from algebra to abstract zoology and marine biology (categorized under biology). The diverse subject content provided participants with different perspectives from their colleagues and helped them discover the overlaps in their methods and objectives.

3.2 Curriculum

CAPSULE professional development is a two-week course that takes place in July. The high level over-

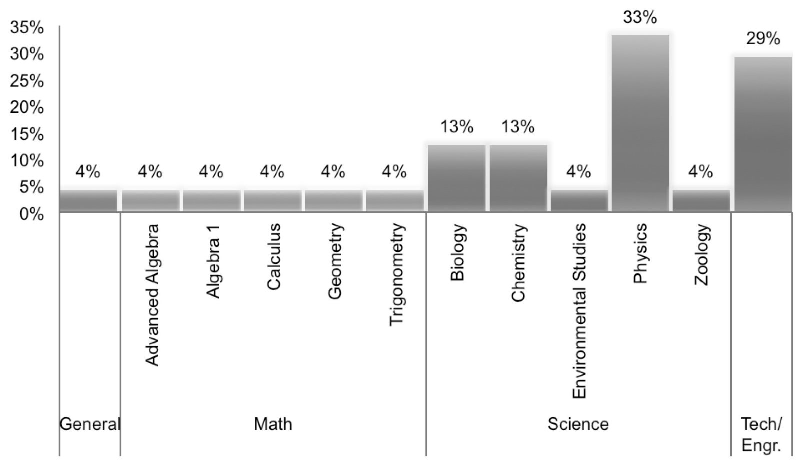

Fig. 2. Participants' school demographic.

Table 1. CAPSULE professional development schedule at a glance [17, 18]

Day	Date	Theme	Location
1	Monday (Week 1)	Engineering-design process and capstone introduced	Northeastern University
2	Tuesday (Week 1)	Manufacturing and CAD	Northeastern University
3	Wednesday (Week 1)	Capstone project skills and tools	Northeastern University
4	Thursday (Week 1)	Practice the engineering-design process and capstone experience	Northeastern University
5	Friday (Week 1)	Capstone project presentations	Northeastern University
6	Monday (Week 2)	Instructional design	Northeastern University
7	Tuesday (Week 2)	Resource exploration	Northeastern University
8	Wednesday (Week 2)	Research and design	Museum of Science
9	Thursday (Week 2)	Instructional research and design	Northeastern University
10	Friday (Week 2)	STEM/capstone action plan presentations	Northeastern University

view of the course curriculum is shown in Table 1. The first week engages participants in a mini capstone experience and teaches them engineering-design process methodology and related tools. In the second week, the teachers apply these tools to their respective subject matter and prepare implementation plans to suite their classrooms.

Participants can take CAPSULE as either a 3-credit graduate course or a professional development certified units, both from Northeastern University. Participants receive a stipend for attending the two-week course and are required to attend two mandatory callback sessions held in January and April of the following year to assess their implementation progress. The purpose of the callback sessions is to continue to build a community of CAPSULE participants, maintain relationships with colleagues, and to assist the participants with difficulties in implementation. Further, callback sessions provide an experience to share student feedback and student learning.

During Week 1, we immerse participants in learning, understanding, (and eventual memorization) of the engineering-design process as a methodology and approach to any project or problem that they encounter during this course and in their classrooms. Week one begins with a hands-on activity of designing a three-legged chair. We then follow it up with analysis and discussion about the experience. The CAPSULE methodology provides the teachers with a systematic methodology for thinking about design, engineering, and problem solving. The main objective of the CAPSULE course is to raise awareness of the capstone experience and the criticality of relating theory to real-world applications for students.

The CAPSULE course covers five different modules (see Table 2) in ten days of the professional development course. Each module builds upon the previous one, emphasizing different aspects of the CAPSULE methodology.

Table 3 provides a detailed list of pedagogical

Table 2. Research modules and topics

Modules	Topics
Engineering-design process	Problem-based learning Capstone inquiry University capstone projects Industry speakers
Manufacturing	Product life cycle Manufacturing processes Manufacturing clinic
CAD / Solidworks™	Modeling in a virtual environment CAD part vs. Assembly 3D model analysis (stress, strain) Engineering drawings
Capstone experience	Engineering-design process and design process Open-ended problem solving Constraints Teamwork Research posters and presentations
Implementation plans	Target course / lesson plans Capstone experience in classrooms Resource exploration CAPSULE alumni (successes, issues) individual capstone action plan presentations and poster session

Table 3. Pedagogical features associated with CAPSULE topics

Phase	Lecture	Homework assignments	Open-ended problem solving	Critical thinking	Project-based learning	In-class team tasks	Formative evaluation	Summative evaluation
Engineering-Design Process	√	√	√	√	√	√	√	√
CAD / Solidworks™	√	√	√	√	√	√	√	√
Capstone Experience	√		√	√	√	√	√	√
Implementation Plans			√	√			√	√
Manufacturing	√					√	√	√

techniques used throughout CAPSULE. These pedagogical activities provided participants with true capstone experiences and opportunities to face problems relevant to daily life. This allowed participants to learn and understand independently and share their understanding with their colleagues.

4. Evaluation and data collection

4.1 Pre- and post-evaluation

The teachers' pre- and post-surveys were developed by the CAPSULE team and evaluated by an external independent evaluator of the program. Participants completed surveys in test format to accurately assess their pre- and post-CAPSULE knowledge and conceptual understanding of material learned. Both the pre- and post-surveys were anonymously conducted but were paired using anonymous identification codes. The pre-survey measured participants' prior knowledge with the engineering-design process, CAD, capstone projects and manufacturing process. The post-survey measured participants' newly acquired knowledge pertaining to engineering-design process, capstone projects, CAD and STEM education resources. We developed these pre- and post-surveys to assess the gains the participants made in the knowledge of main topics taught during the course.

4.2 Formative surveys

As part of the CAPSULE evaluation plan, CAPSULE participants completed surveys at the end of each day. The daily surveys are designed to be short and concise to capture feedback related to that day. These daily formative surveys allowed the CAPSULE team to assess participants' perception and reflection of activities, lectures, PBL, and additional components of the professional development. The first week, daily surveys were primarily open-ended questions that asked participants to reflect on thoughts and understanding of the day's topic. In week two, daily surveys also contained Likert-scale items that assessed participants' understanding and perception on their comprehension of various topics.

4.3 Data coding and analysis

We used NVivo9 software to code the qualitative data into an organized and understandable thematic structure. This software creates a hierarchical node structure to develop and seek relationships amongst piles of qualitative data. NVivo9 has allowed us to categorize data into overarching themes to provide a better understanding of where the majority of participants are classified. Fig. 4 presents the results for Question 3 from Day 1 (Parent Node. D1Q3). Question 3 reads as "The three legged chair activity was a useful way to kick-off the CAPSULE program. Some of the things that I'm thinking about now about the Engineering Design Process are (as a result of the Three Legged Chair activity) . . ." The themes listed below are the classifications of participants' comments from Day 1 in response to Question 3. Our qualitative data was coded with a hierarchal system with the parent node as the top tier (shown in Fig. 3) using Day 1, Question 3 and the categorized response of "Incorporating projects into high school classes".

As shown in Fig. 4, 61% commented on the implementation of the activity into their own classrooms. The uniqueness of coded qualitative information is that themes and metaphors become apparent; it provides a good perspective of what participants think, believe and are concerned about. It allows for the participant to drive the research because the responses are open ended.

To evaluate participants' comments further, individual nodes need to be analyzed in relationship to other nodes. Qualitative data is organized from a broad to specific level. Table 4 presents the comments and concerns from participants who responded to the theme "*incorporating projects into high school classes*". By having the ability to view all comments related to one theme, it provides researchers (CAPSULE team) insights into partici-

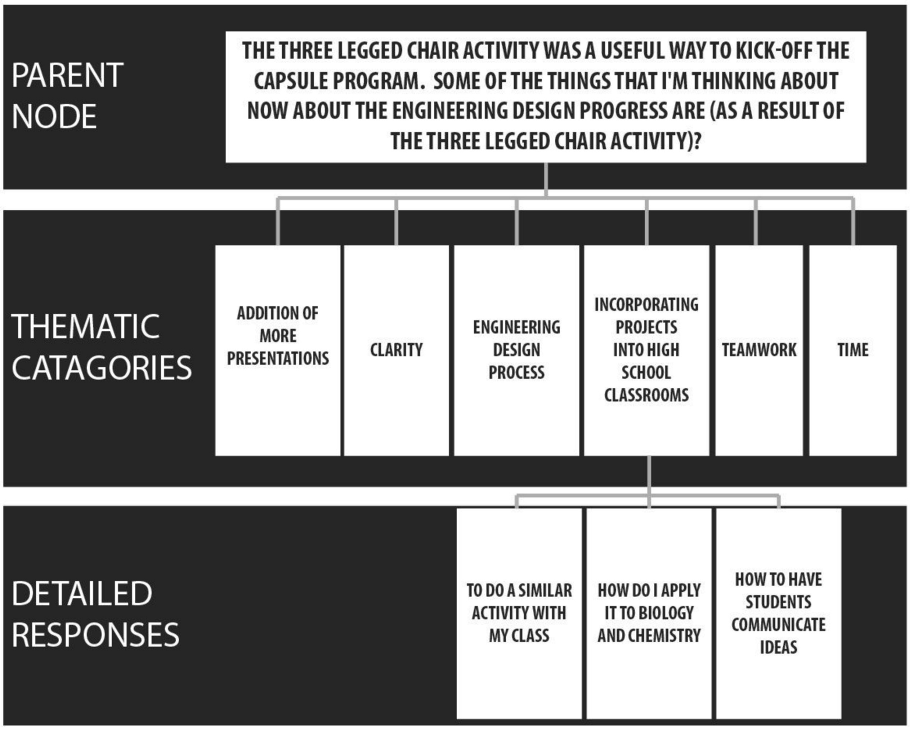

Fig. 3. Hierarchal system describing node structure.

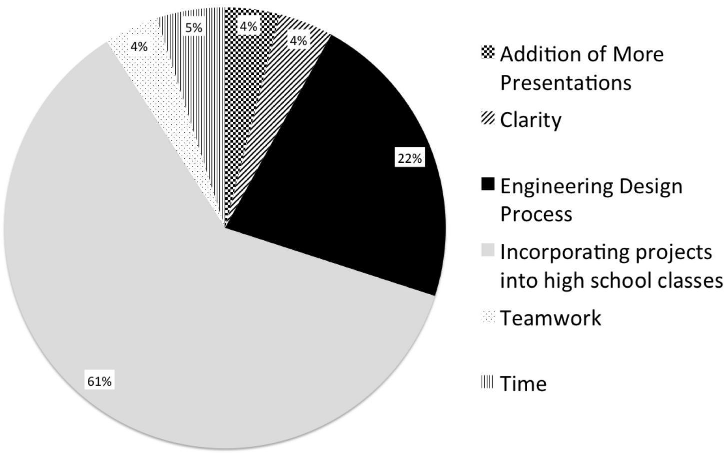

Fig. 4. Example of Day 1, Question 3 theme results.

Table 4. Participants' response to theme "Incorporating projects into high school classes"

Comments	Concerns
Definitely applicable to class. This has sparked my interest to incorporate other engineering-design process lessons.	How does this process fit into my math class and what are the natural intersections of math and science?
To do a similar activity with my class.	What needs to be a first step so that my students can benefit from the process with minimal confusion?
How to have students communicate ideas.	How do I apply to biology/chemistry?
I would definitely do this activity. I love that this is a real human-scale product.	How can I fit the necessary time into my curriculum to really do justice to the design process?
	How to incorporate capstone activities in my physics course?
	Having my students explore materials to use in designing green products.

pants' thoughts and feelings towards this activity. Because the data was collected anonymously, participants had the freedom to express their thoughts and opinions. This kind of openness is not possible in focus groups or one-on-one interviews. This process eliminated almost any research bias in the responses.

After analyzing these comments, we readjusted the program activities to address primary concerns the following day. For example, we responded in a timely fashion to the participants' concerns regarding how the CAPSULE methodology can be incorporated into different STEM subjects. In addition to qualitative analysis, the CAPSULE program was also supported by an external evaluator who performed the summative evaluation in small focus groups throughout the summer program and during the callback sessions.

The post-survey was conducted on the final day of the course regarding the concerns and the knowledge gained through the ten days of the course. There were also three open-ended items on the post-survey that asked teachers to describe what aspects of the course they found most valuable, recommended changes, and additional comments. Furthermore, a selected group of teachers participated in a focus group covering a range of topics such as what components they felt they would benefit from in their teaching practice and what aspects were most challenging or frustrating.

5. Implementation and delivery

Each day the CAPSULE program had an overarching theme. On Day 1 of Week 1 the theme was familiarizing participants with an engineering-design process. For many participants, this was the first time they had experienced an engineering-design process through the three-legged chair activity (see Appendix A). By experiencing an engineering-design process without formal instruction, participants were able to understand commonalities instinctively. The purpose of this activity was to provide participants with an understanding that solving a problem is doing engineering. When final design solutions are displayed, we proceeded to test each chair to determine if it could withstand the weight of an individual. The intention was to show that simple materials such as duct tape and cardboard can be used to create a durable, functional prototype in addition to the variations of results that are produced from a simple open-ended challenge (see Appendix A).

Day 2 of Week 1 was all about the introduction of technology and manufacturing to participants. They experienced a manufacturing assembly line that built desktop clocks while learning the math principles behind manufacturing efficiency. This activity provided them with a sense of a manufacturing line and how everything in manufacturing is related to math and science concepts. Participants were exposed to cycle time and manufacturing lead time algorithms to maximize production rate and line efficiency and minimize the production cost.

Day 3 and Day 4 of Week 1 were marked as learning and working days. Participants used their knowledge and skills to solve the open-ended problem of the "Office Bookcase" (see Appendix B). These days were designed to use newly acquired knowledge to create something real and tangible immediately. In spite of their less than matured skills, teachers were able to build and create a reasonable solution to the problem. Day 5 was the "Capstone Day" where participants were able to experience what the culmination of a capstone experience was like. During the morning, participants experienced "judging" of their posters, their methods, their possible solutions and final designs. Everyone had a chance to walk around, observing each other's posters and final solutions. This process and experience is very similar to what happens during a college capstone presentation session. The intention of providing time for participants to compare solutions is to emphasize multiple solutions to the same open-ended problem.

Day 1 and 2 of Week 2 gave participants opportunities to take the tools and lessons learned from Week 1 and apply them to prepare implementation plans for use in the classroom and capstone experiences for their students. On Day 1 of Week 2, the theme was instructional design. This included understanding how the CAPSULE curriculum and the classroom curriculum were connected through the Massachusetts State Framework and Common Core. Additionally, participants were taught how to form a feasible and reasonable action plan. The primary purpose of Day 1 of Week 2 was to determine and identify target course/lesson plans, target teaching challenges, and identify the skills and tools needed to establish starting points of these implementation plans. Participants were exposed further to capstone project examples and engineering-based curriculum design through CAPSULE alumni. Participants were also exposed to cross mapping of STEM content and challenges by working in teams of similar subject content to develop research plans and work on content pedagogy and capstone learning style.

On Day 2 of Week 2, the participants continued to explore information regarding free and/or inexpensive resources. The theme of Day 2 of Week 2 was resource exploration and development of classroom implementation plans. Participants were given the implementation plan poster template to begin to visualize main topics of their action plans. Day 3 of Week 2 was held at the Museum of Science (MoS) to give participants an opportunity to explore additional research material and design resources. The activities of Day 3 or Week 2 reinforced state standards and benchmarks as well as gave chance to explore MoS technology curriculum collection and new curricula resources. At the museum the participant also learned about designing exhibits and green engineering.

On Day 4 of Week 2 the participants focused on instructional research and design. The day was designed for collegial collaboration, brainstorming and discussion. It was a chance for participants to converse with colleagues and CAPSULE team members on how to modify and create a curriculum for specific lesson plans or specific courses. The final day (Day 5 of Week 2) was all about individual final presentations on how participants were going to implement what they have learned into their classroom. Each participant presented their poster and handed in written implementation plans and the respective grading requirements for their students.

6. Results

Week 1 had two main deliverables, the completion, testing, and presentation of the three-legged chair (see Appendix A) and the final capstone poster and presentation displaying their methodology of the capstone design solution (the redesign of the office bookcase). The three-legged chair design exercise demonstrated that the engineering-design process is an intuitive process and is not an entirely new concept to learn. Participants were divided into teams and were given Monopoly™ money as a budget. After the completion of the design using the engineering-design process, teams purchased their desired materials from the "store". The three-legged chair activity used all recycled materials from the Boston Recycling Center (a free source of material) to construct and build their designs. This activity was supposed to represent a mini capstone experience without the formality or knowledge of the tools, resources, and process that would be introduced later in the week. A few snapshots of the activities from the brainstorming to construction of the three-legged chair are shown in Fig. 5. Given that a three-legged chair can be built with a variety of materials, many teachers used this activity in their classrooms to connect STEM concepts in their classroom to the design and construction of the chair.

The second deliverable of Week 1 was the final capstone presentation. Participants were again divided into new groups and asked to solve the problem of the office bookcase (see Appendix B). Teams were given constraints, both functional and aesthetic as well as stress and strain requirements on the individual shelves. This experience forced participants to use the tools they had learned such as CAD and the engineering-design process to create a unique solution to the given problem. Teams had to produce a final poster and a PowerPoint™ presentation documenting their methodology, how and why they arrived at their final design, lessons learned during the evaluation of the final design and how to refine the final design if provided the opportunity to do a redesign. For many participants, this was the first relevant experience in which they took a real-world problem and successfully solved it by applying relevant STEM principles. Fig. 6 gives examples of the office bookcases participant teams created in response to this assignment.

Participants reported that they have a new appreciation for the multiple uses of Solidworks™ and that it is more than modeling software. The bookcase challenge also yielded a better understanding and realization of how intertwined STEM courses are to each other from material science to physics and geometry. Participants also realized the importance of virtual modeling and redesigning to determine the best solution given the constraints. For many participants, they had forgotten how to struggle with something new to them. They realized that cooperation and perseverance of individuals are keys to success in learning EDP and Solidworks™. Further, participants realized the significance of collaboration among team members, leading to new and better ideas. Each teacher brought his or her expertise and strengths to brainstorming process and collaborative work. Partici-

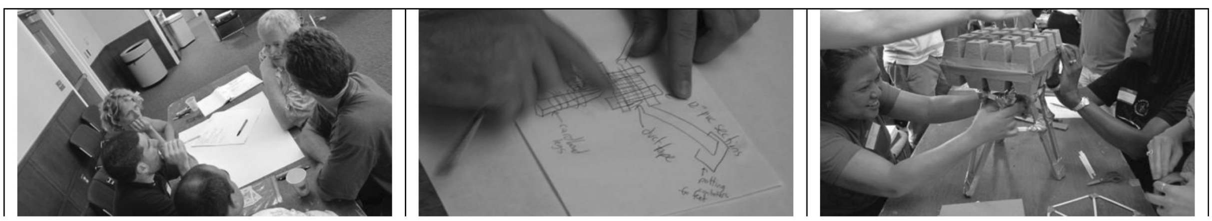

Fig. 5. Three-legged chair brainstorming, design, and construction.

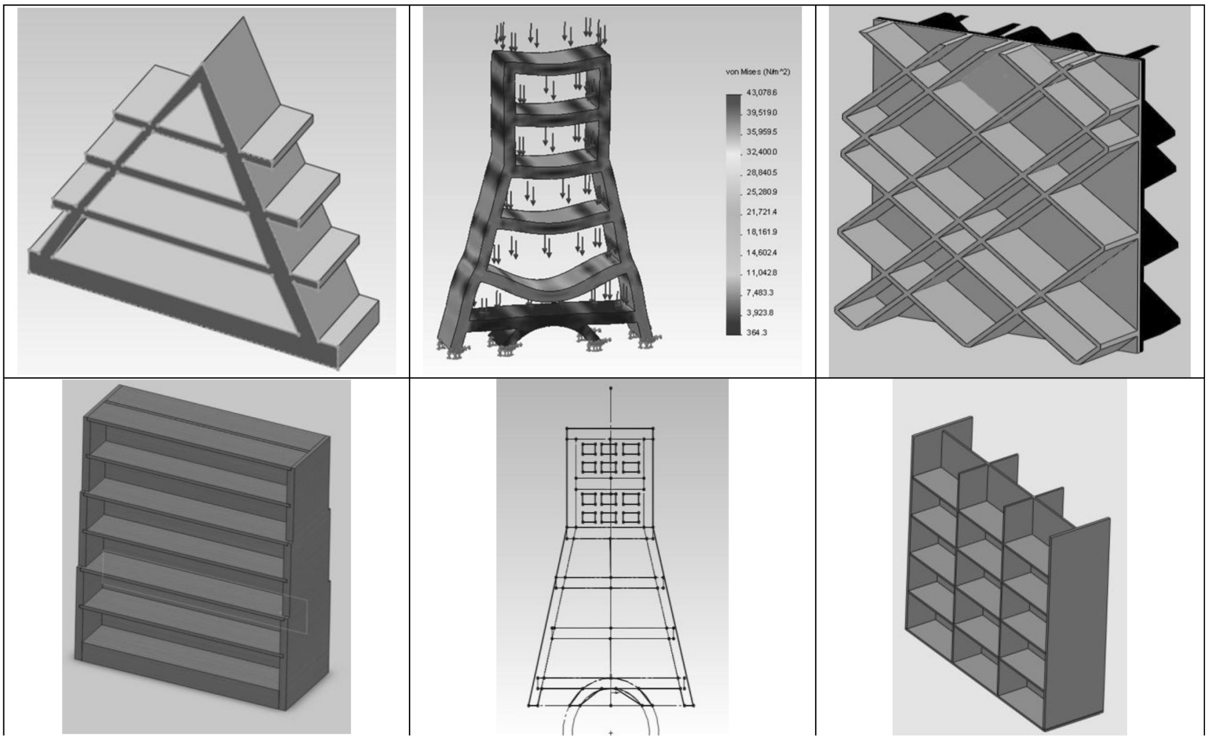

Fig. 6. Bookcase solution Solidworks™ models.

pants also realized how much time, effort, and willingness it takes to find a reasonable, logical solution to a given problem.

Figure 7 is an example of a team's capstone poster. This team had created an accordion bookcase that could be folded or expanded depending on the user's needs.

In Week 2 participants entirely focused on writing and refining their implementation plans. The participants asked questions, collaborated with the CAPSULE team and colleagues to identify projects that potentially have success for implementation. For the final deliverable, participants focused on creating individual implementation posters and project plans integrating CAPSULE methodologies in their classroom. Week 2 provided the participants with opportunities to reflect on the upcoming school year and how the CAPSULE methodology, engineering-design process, and capstone experience were going to impact their classrooms. Fig. 8 presents the implementation poster of a biology/zoology teacher and her proposed plan to integrate EDP and Solidworks™ into her curriculum.

Similarly, a math teacher created his implementation plan around speaker design, building and prototyping. Using Solidworks™, students will design and virtually analyze the stress and strain properties of their design. This math teacher created an implementation plan that will teach students the engineering-design process for designing a speaker as well as teach them that the engineering-design process is universal regardless of the proposed problem. Additionally, a second project will involve the design and analysis of a stool.

In Week 2 participants are expected to deliver implementation posters, presentations and final reports that include grading evaluation policy. Participants were assessed on their homework, capstone project and action plan submissions. Participants implemented the capstone experience to reflect their own classroom needs. For example, some participants created lesson plans to aid student understating in certain STEM concepts individual to the student. While others used a capstone project in a course where students solve a problem and design a solution, similar to the capstone experience in CAPSULE. Lastly, a few teachers chose to dedicate one semester-long course to teach the capstone experience and CAD at the high school level.

7. Discussion

Student improvement, motivation and educational experience are the utmost priority in the education system. Students only learn what their teachers and educators know and teach. Education is a continuous cycle of learning, understanding and self-improvement to provide a beneficial educational experience for students. Through CAPSULE, participating teachers made the connection between the

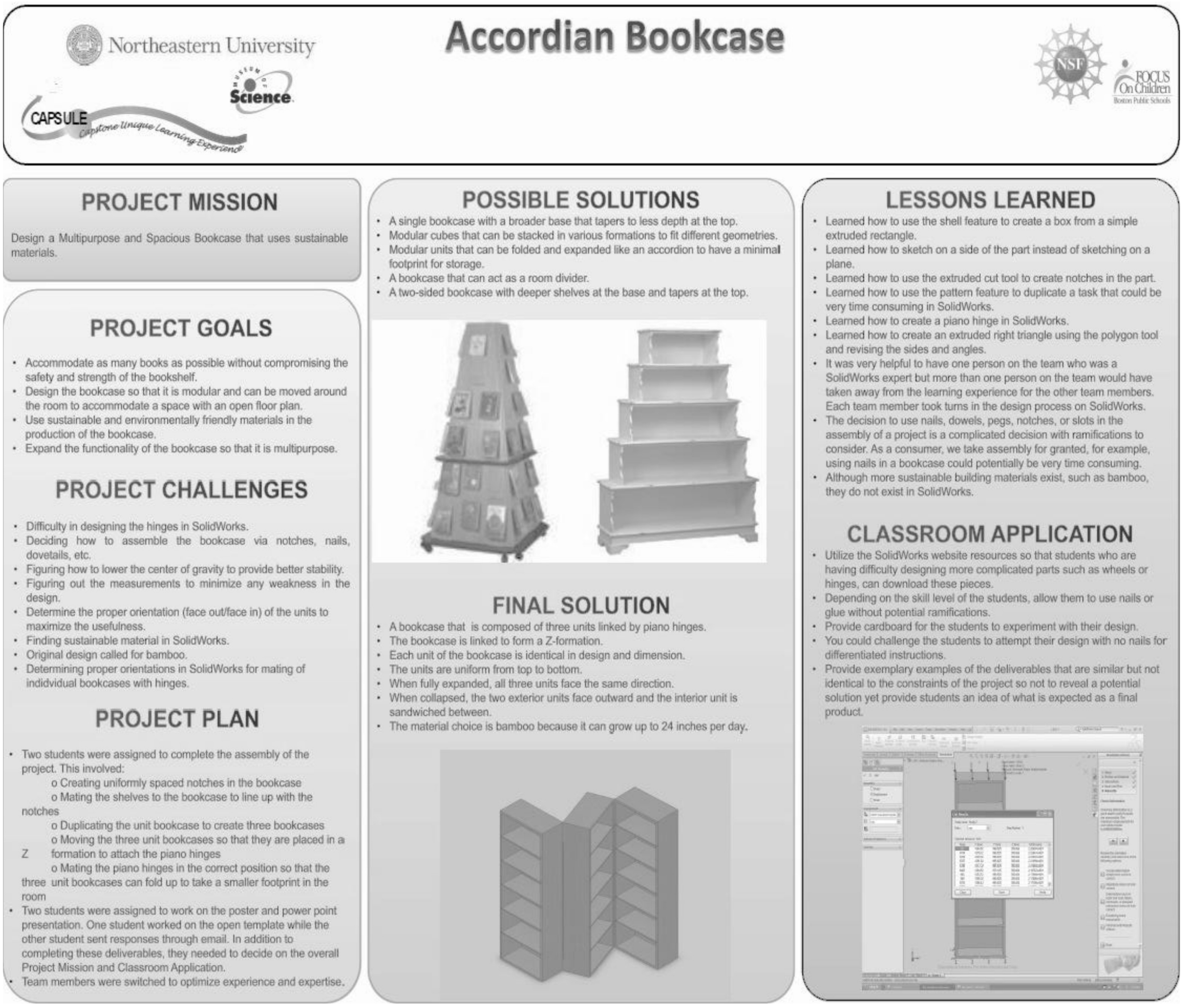

Fig. 7. Example capstone poster.

concepts taught in their classroom, project-based learning, engineering-design process and application. The CAPSULE study findings corroborate the need for real-world examples to reinforce basic STEM principles. The results suggest that with a simple, everyday product such as a bookcase, participants were able to connect the engineering-design process with the process of designing and developing the bookcase as well as math and science principles pertaining to stress and strain analysis.

Through the first and second years of CAPSULE, we gained valuable insights into high school educators learning process and understood the differences between high school teaching and teaching at the university level. For one, the constraints at the high school level are much more restrictive than at the college level, specifically with regard to flexibility of time, mandated state and national education standards and most importantly, limited funding. Further, high school teachers not only act as educators but also act as mentors and in some cases act as a second or third parent, teaching and guiding young individuals about life, in and out of school. By better understanding teachers' constraints, we can modify and design appropriate professional development programs for them. The results from this study have shown the importance and applicability across all STEM disciplines. The benefits of CAPSULE on student learning have supported the idea that we can change student and teacher perceptions of STEM theory versus STEM application.

For many participants, CAPSULE was the first opportunity to experience a true capstone experience. Although it was virtually a two-day capstone project, participants worked at an extremely high, productive level with new colleagues to produce unique and creative bookcases. Our findings show that in a short time, with direct and succinct education on tools and resources, teachers are able to produce real-world products with basic knowledge of industrial level software. Teachers reported that

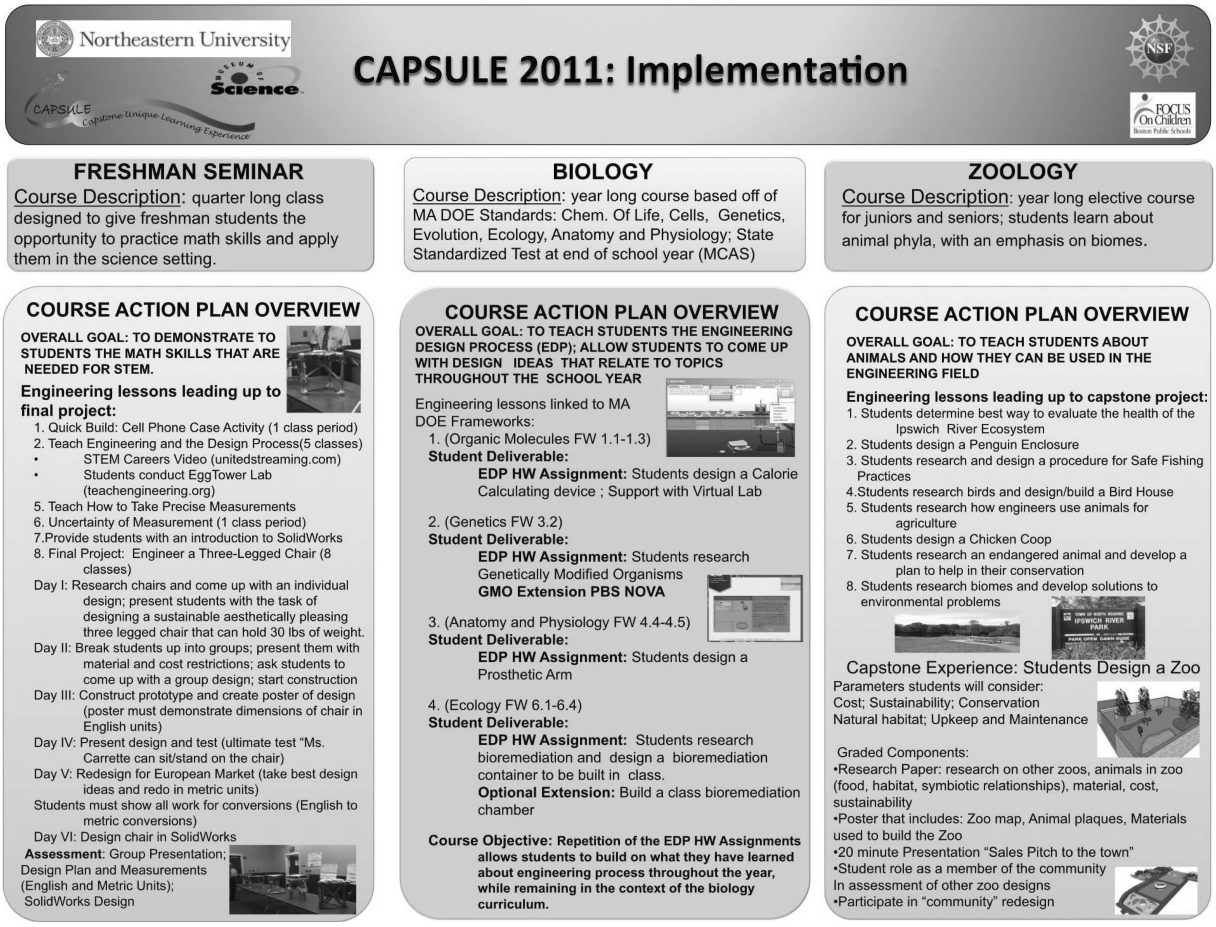

Fig. 8. Example implementation poster.

their struggle with learning new tools and determining new solutions is similar to that of their own students experiencing frustrations.

The participants were frustrated during the initial period of learning about resources and tools. In contrast, the final day before their final presentations teachers displayed unexpected competency and fluency in the CAPSULE approach. On each Thursday (Day 4 of Week 1 and Week 2), everything participants have learned had come full circle in both their capstone presentations and their implementation posters. Similarly, many participants reported hearing similar complaints from their own students, observing positive and negative student learning outcomes when new material was introduced. Participants got an opportunity to really struggle with a problem, something that is rarely seen in the classroom today. This strategy was necessary by virtue of the steep learning curve involved in mastering the engineering-design process, and learning Solidworks^{TM}.

Day 4 and 5 of Week 1 were used for final capstone preparation and subsequent poster session. Participants had the opportunity before presentations to walk around and read about other teams' methods, alternative designs and final designs. Many groups also presented lessons learned and the challenges throughout the process. Day 5 showcased the capstone experience, from anticipation to presentation by unifying as a group to finalize the solution, presentation and poster. For many participants, it had been a significantly long time since they had worked so closely in groups to create and evaluate a solution to a problem. This first week's experience provided participants with a scaled-down experience of what undergraduate students go through in the final year of college. The activities of this week emphasized open-ended problems that could have multiple solutions and surprisingly, multiple solutions could meet the constraints of the problem. Further, Week 1 emphasized creativity within STEM courses, concepts, and exploration of other measures of knowledge. One participant reported during a callback session that his students who typically do not perform well on exams thrived using the engineering-design process. Not only did those students perform better, they also understood and related math concepts to their own lives. It is inevitable that people, teacher or student gravitate toward things that they find enjoyable, regardless of whether it is food, music or learning. By applying the engineering-design process to everyday problems, teachers were able to help students better understand how high school classes, especially STEM classes are all intertwined in their life.

The capstone experience was a first experience for many participants. It was a new experience working very quickly with new colleagues while still learning new tools. Similar to any high school classroom environment, some teams were efficient and effective in dividing and conquering each task, while others experienced common frustrations due to poor communication, overbearing, and over controlling team members. All teachers saw an important connection between the curriculum and real-world relationships and vowed to incorporate part or all the CAPSULE methodology into their subject content. Despite this fact, there are still a number of first order implementation barriers such as funding, material, time, and state standards.

Many educators were out of their comfort zone and experienced again what it was like to be a student and feel the frustrations of students. One of the insights gained from participants is that students' learning should include opportunities to struggle with a problem; challenging problems lead to a better understanding with students' perception of new material. Additionally, formative survey evaluation results exhibited that the majority of participants better understood real-world relationships to STEM theory. Participants also reported that they felt they better understood how to use capstone experiences and the engineering-design process to enhance the quality of learning for their students. For many participants, the engineering-design process provided them with a structured process that students could follow to create a solution and at the same time be creative and break from a typical mold.

The engineering-design process allowed many participants, who were unsure or cautious about the added value of the capstone experience to see an organized method that has previously worked at the collegiate level. While participants felt concerned about their own competency and expertise with the open-ended approach, they managed this concern by conversing and learning in groups and losing their fear of asking questions.

The engineering-design process provided a structured approach to teachers. One of the participants developed a "Phloat your Boat" curriculum module that is geared toward senior-year physics classes. "Phloat your Boat" is a curriculum designed to research, design, build, and analyze boats with a strong focus on fundamental physics principles. This course module is designed as a fourth term, physics capstone project where students are given the task of building a boat given varying constraints, requirements, rules, and guidelines. Students learn and see principles at work such as center of mass and torque, buoyancy, and how materials affect floatation. This participant's primary goal was to cater to the at-risk populations in her comprehensive high school. The involved school has done the "Phloat your Boat" curriculum for approximately 10 years; however, it lacked concise direction and structure. Her ultimate goal was to formalize the project into a capstone experience using the engineering-design process as the foundation methodology.

This structure and methodology using the engineering-design process is something that this participant had never used on open-ended projects. She was unable to implement these projects in a structured manner well enough to confidently report that the students were learning and absorbing more information than in traditional lecture mode. With the engineering-design process, she has since mapped each stage of the "Phloat Your Boat" curriculum to the different steps of the engineering-design process. This mapping allowed students to understand the process of finding a solution rather than just carrying out a project.

Another participant focused on exposing students to STEM and the engineering field in courses such as freshman biology, zoology, and applied math in a science freshman seminar. Specifically, this participant wanted to implement the engineering-design process in the freshman zoology seminar course. We found that biology and chemistry are particularly difficult subjects for which to create EDP based projects. These subjects are difficult primarily because EDP leverages Solidworks™ in its methodology. Solidworks™ is an unconventional program used with these particular sciences. Despite this difficulty, understanding and using the engineering-design process still integrates into their curriculum.

8. Conclusion

The results of the CAPSULE study indicate that teachers' perceptions of engineering and student learning have been altered by their participation in the CAPSULE program. The program has also shown evidence of influencing their pedagogical practice in the classroom. This is particularly important in light of the original issues posed in this study. If teachers' pedagogical beliefs and practices are dictated by professional enrichment and development, then it is extremely important to understand how to refine programs to reduce the steep learning curve, especially when it comes to assimilating technology in the classrooms. In other words, successful and widespread integration of the open-ended approach depends on discovering effective ways to help teachers to become comfortable with iterative learning, 3D modeling, and engineering-design process. Although there have been positive results, this study has some limitations too. One of the limitations is the fact that we worked with teachers as surrogates as oppose to directly working with students. Working with teachers rather than students affects how information is transferred and the method impacts student perception of STEM. Similarly, most of the feedback we received from teachers was qualitative so, in translating them, some of the precision could be lost or the intent of the comments not captured precisely. Overall, teachers and students appeared to benefit tremendously from the use and implementation of engineering-based teaching and learning model in the classroom. The necessity of relating STEM theory to application is an opportunity to teach students career and industry possibilities. Over two years of professional development observation, classroom observation, and data analysis, we believe the adoption of the engineering-design process is critical to promote STEM careers.

Acknowledgement—This work is supported by the National Science Foundation under grant numbers DRL 0833636. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Appendix

A.2 Appendix

Design Challenge Activity for Day 1
Design a three-legged office chair

Description

Picture this for a moment. You are an engineer working for a company called Product Innovation Corporation (PIC) with headquarters in Boston, Massachusetts. You work for the company Design Department. PIC specializes in designing and manufacturing office furniture such as chairs, tables, etc. PIC is an environmentally conscious company. Your design team is charged by your company to produce a sustainable design of an office chair, i.e. minimize the impact of the chair design on the environment. Within this context, your team must come up with a design that minimizes the material used to make the chair.

Design goal

Design a chair that uses the least amount of material.

Design specs

Chair must:
- use only three legs;
- be stable and safe; i.e. chair would not fall backward or sideway easily;
- support a maximum weight of 300 lb. (as much weight as possible for the construction-material-based prototype);
- be aesthetically pleasing;
- be comfortable;
- have arm rests;
- have a back;
- promote healthy posture, i.e. forces the user to sit straight without arching their back.

Design constraints

Chair must:
- use the least amount of material;
- cost under $150;
- be recyclable at its end of its life.

Team work

Your design team consists of two designers, you and another teacher.

Design time

You must finish your design within 60 minutes.

Design resources

It is up to you and your team members.

Deliverables

- A three-legged chair prototype
- Two minutes per team to pitch their design to PIC customers (us in the room)

A.2 Appendix

Capstone Project
Design a sturdy bookcase

Description

As you did in the design challenge on the first day, you still work for the PIC Design Department. Your design team is charged by your company to produce a sustainable design of an office bookcase, i.e. minimize the impact of the bookcase design on the environment. Within this context, your team must come up with a design that minimizes the bookcase material.

Design goal

Design a durable and sturdy bookcase.

Design specs

Bookcase must:
- not exceed a space envelope of 5 feet wide × 8 feet high × 2 foot deep;
- be stable and safe; i.e. bookcase would not fall easily;
- each shelf be as strong as possible;
- be aesthetically pleasing (e.g. use boxed design, curved-contour design, etc.);
- have a back.

Design constraints

Bookcase must:

- use the least amount of material and be as light as possible (volume calculations);
- have a sustainable design (sustainability calculations using at least two material options);
- cost under $100;
- provide the maximum shelf space as measure by the number of books it can hold (use a book size of 8 inch wide $\times$ 10 inch high $\times$ 1 inch deep);
- use a low center of gravity as much as possible for safety concern (centric location);
- provide maximum shelf strength (stress analysis) for maximum load carrying capacity.

Calculate the factor of safety of the shelf.

Team work

Your design team consists of three designers, you and two other teachers.

Design resources

It is up to you and your team members.

Deliverables

- A written report
- A CAD prototype (included in the report via screenshots)
- Slide presentation
- Poster

Tools and skill set

Math, geometry, and physics concepts; written and oral communication skills; engineering-design process; Web search for ideas; and Solidworks CAD (3D modeling, volume, FEM/FEA, sustainable design, prototyping).

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