Student Understanding of the Engineering Design Process Using Challenge Based Learning

Dr. Whitney Gaskins, University of Cincinnati

Dr. Gaskins joined the Engineering Education Department in 2014 as visiting professor. She earned her Bachelor’s Degree in Biomedical Engineering from the University of Cincinnati in 2008. Whitney earned her Masters of Business Administration in Quantitative Analysis from the University of Cincinnati, Lindner College of Business in 2010. She earned her Doctorate of Philosophy in Biomedical Engineering/Engineering Education also from the University of Cincinnati. Her dissertation "Changing the Learning Environment in the College of Engineering and Applied Science: The impact of Educational Training on Future Faculty and Student-Centered Pedagogy on Undergraduate Students" was the first of its kind at the university. Whitney has been recognized by the National Technical Association (NTA) for her novel approach to studying students, specifically underrepresented minorities and women. Whitney also works with the Emerging Ethnic Engineers (E3) Program. She teaches Calculus 1 during the Summer Bridge program and instructs Cooperative Calculus 1 during the school year.

Continuing with her commitment to community involvement, Whitney has previously served on the National Executive Board for the National Society of Black Engineers, a student-managed organization with more than 30,000 members. She served as the Planning Chairperson for the 2013 Annual Convention and is currently an advisor for the Great Lakes Region.

Dr. Gaskins the Vice-President of the Sigma Omega graduate chapter of Alpha Kappa Alpha Alpha Sorority, Inc. She is also a member of the Society of Women Engineers, the Women’s Alliance, the National Technical Association, The Biomedical Engineering Society and the National Alliance of Black School Educators amongst other activities. She is Deaconess at New Friendship Baptist Church. Whitney was recognized in the 2013 Edition of Who’s Who in Black Cincinnati.

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Dr. Catherine Maltbie, University of Cincinnati

Dr. Cathy Maltbie is a Research Associate jointly appointed at the University of Cincinnati Evaluation Services Center and the Arlitt Child & Family Research & Education Center. She has a BS in Chemical Engineering and an EdD in Educational Studies with a concentration in the cognitive and social aspects of instructional practices. Dr. Maltbie has evaluated STEM educational projects and programs since 2000.

Ms. Julie Steimle, University of Cincinnati

Julie Steimle is the Project Director for the Cincinnati Engineering Enhanced Math and Science Program (CEEMS). Prior to that, she ran an outreach tutoring program for K-12 students at the University of Cincinnati. Before joining UC, Ms. Steimle served as the Director of Development and Children’s Services at the Literacy Network of Greater Cincinnati. She graduated from Thomas More College with a bachelor’s degree in English and Secondary Education.
Student Understanding of the Engineering Design Process Using Challenge Based Learning (RTP – Strand 1)

Abstract

In this study conducted in a large metropolitan city, teachers introduced and implemented CBL in the curriculum. One research objective of the study was to teach middle and high school students the engineering design process (EDP) while solving a real world challenge using Challenge Based Learning (CBL). The EDP is the formulation of a plan to help an engineer build a product or formulate a process with a specified performance goal. Because there are performance characteristics as well as constraints, there will typically be a variety of potential solutions. EDP involves a number of steps, and parts of the process may need to be repeated many times before production of a final product can begin. Students were asked to draw their understanding of the EDP at the conclusion of the CBL curricular Unit. Specifically, we observed the nature of students’ misconceptions and the effects CBL pedagogy has on conceptual understanding of the EDP.

For assessment the important elements of EDP are:

1. Correct terms are used
2. Terms are connected to each other
3. Terms are connected to each other in the correct order
4. Cyclical Representation of EDP is identified

At the end of a CBL-EDP curricular Unit taught by a teacher, students were asked to complete a questionnaire which included a question asking them to illustrate their understanding of the way they implemented EDP in the Unit through a drawing. These drawings were interpreted for the elements listed above. To date, a four person team of trained scorers used a rubric to score EDP drawings from 6 out of 34 teachers (17.6%); this included 518 EDP drawings out of 4545 received (11.4%). Individual teachers had differing numbers of students in their classes. The four scorers had three training sessions and two scorers rated each drawing. In this paper, the training of the raters, the evaluation process used by them to score the EDP drawings made by the students, the results of their findings, and statistical technique used to validate the results are presented and discussed. As discussed later in the paper, our inter-rater reliability was 0.90 - 1.94 using Cronbach Alpha statistic for each pair of raters.

Initial rubric scores indicate that the students can identify the steps in the EDP process and understand that they are connected. However, it is found that they are not representing the cyclical nature of EDP and the correct order of the steps. Since these results are a reflection of the teachers’ Unit implementation, we will work with the project team and resource team to support professional development for the teachers to improve their CBL and EDP instruction.
Introduction

Next Generation Science Standards (NGSS), as defined by the National Research Council (NRC), include the critical thinking and communication skills that students need for postsecondary success and citizenship in a world fueled by innovations in science and technology\textsuperscript{20}. These science practices encompass the habits and skills that scientists and engineers use day in and day out. Ohio’s New Learning Standards for Science lists the highest cognitive domain as “designing technological/engineering solutions using science concepts”\textsuperscript{20}. This “requires students to solve science-based engineering or technological problems through application of scientific inquiry. Within given scientific constraints, propose or critique solutions, analyze and interpret technological and engineering problems, use science principles to anticipate effects of technological or engineering design, find solutions using science and engineering or technology, consider consequences and alternatives, and/or integrate and synthesize scientific information”\textsuperscript{21, 22, 23}. The report: Engineering in K-12 Education: Understanding the Status and Improving the Prospects advocates for a more systematic linkage between engineering design and science inquiry to improve learning\textsuperscript{16}.

Furthermore, the new Common Core Math Standards call for students to practice applying mathematical ways of thinking to real world issues and challenges. Those real world challenges naturally exist when engineers use math to explain science and design technologies, products, and processes to positively impact society\textsuperscript{6}. Ohio adopted the new standards on June 18, 2010 for full implementation to take effect the 2013-2014 school year\textsuperscript{21}.

Research has shown that student-centered learning approaches are efficacious in improving student learning\textsuperscript{11}. In particular, the challenge based learning (CBL) methodology proposed by Apple Computer, Inc., employs a multidisciplinary approach in encouraging students to use their knowledge and technology to solve real-world problems\textsuperscript{12}. In Apple’s 2008 study of CBL, findings showed student engagement among participating ninth and tenth graders was rated at 97% or higher and that student involvement peaked where they perceived the solutions they worked on to be of real value\textsuperscript{7}. In CBL, students are presented with a challenge that requires them to draw on prior learning, acquire new knowledge, work as a team and use their creativity to arrive at solutions. In most cases, CBL connects students to their community because the challenge that they are working on attempts to solve a real-world problem. Within CBL the EDP guides and informs the solution. Because there are performance characteristics as well as constraints there will typically be a variety of potential solutions. Using knowledge gained and knowledge/experiences they bring with them to the course, students in groups identify the best alternative and implement the solution. Student teams must also share their solution to the challenge often in multiple formats. Oral, written and visual communication skills should be developed as part of the process. Understanding and judging which media and technologies will be most effective in these presentations is a priori.

In this paper results from middle school and high school students on their understanding of engineering design as taught through CBL is presented. Students are asked to draw the EDP used and each drawing is analyzed and scored according to the project rubric. The development of the rubric and scoring is discussed.
Literature Review

Science for all Americans proposed the idea of “scientific literacy” for all students\(^\text{24}\). The term is usually regarded as being synonymous with “public understanding of science,” scientific literacy will enable individuals to participate more intelligently in the productive sector of the economy\(^\text{29}\). Higher levels of scientific literacy among the populace translate into greater support for science itself\(^\text{27}\).

Mathematics taught in schools has not prepared young people for industry or the university\(^\text{18}\). Schoenfeld\(^\text{25}\) identifies the lack of math competence and ability as a barrier to full participation in the economic mainstream. Mathematical literacy has received increasing attention driven by concerns of employers that too many students leave school unable to function mathematically at the level needed in the modern world of work.

One suggestion of how to help students become scientifically and mathematically literate is to engage them in authentic learning opportunities. The need for authentic learning has been called for in the National Science Education Standards\(^\text{17}\) in the work of the American Association for the Advancement of Science (AAAS)\(^\text{2}\) and the National Science Teachers Association (NSTA)\(^\text{19}\).

In the science education community inquiry design is increasingly being viewed as a gateway to authentic learning that can support increased student learning of scientific concepts. Benenson\(^\text{4}\) argues that system-wide reforms in science event caused by technological demands of society, and he demonstrates how “everyday technology” could be used as the context for promoting scientific literacy. Kolodner\(^\text{14}\) employed a Learning By Design (LBD) approach in which the design process is used as the vehicle for teaching science concepts. It is reported\(^\text{14}\) that LBD students outperform non-LBD peers in ability to design experiments, plan for data gathering and collaborate. Similarly, Mehalik, et al.\(^\text{15}\) suggests that a systems design approach for teaching science concepts is superior in terms of knowledge gain achievements in science concepts, engagement, and retention when compared to a scripted inquiry approach. It was most helpful to low-achieving African-American students.

The link between application of math concepts to students’ everyday lives and improvements in math performance is supported by the theory of situated cognition\(^\text{5}\). Studies consistently find a positive association between teaching math through application and improved performance on tests of conceptual understanding. Authentic activities value the experiences and knowledge students bring with them to the classroom and allow students to learn math in a context that is meaningful to them\(^\text{8}\).

The Next Generation Science Standards\(^\text{20}\) and the Ohio New Standards for Science\(^\text{23}\) both place a high value on teachers integrating engineering design into the science classroom. Recognition of the need for math literate students prompted the National Council of Teachers of Mathematics (NCTM), the world’s largest mathematics education organization, to develop standards for the reform of mathematics curriculum, teaching and assessment in American schools. In addition, while the Common Core Standards\(^\text{6}\) do not specifically mention engineering design, the math practices coincide well with engineering activities focused on math content. By learning to use the EDP students will be better able to approach a broad range of real-world challenges. In many
cases, brainstorming solutions to an engineering design challenge requires creative thinking and both the ability and the confidence to think outside a prescribed set of parameters.

The Program

To address the new standards and bring engineering content to students it is necessary for science and math teacher to understand the nature of engineering and its design process. To ensure students are taught the EDP, teachers who participate in the Cincinnati Engineering Enhanced Mathematics and Science Program go through a 6 week professional development training program called the Summer Institute for Teachers (SIT), where teachers learn about CBL, EDP, NGSS, Ohio New Standards for Science and Common Core Standards while they earn a Certificate of Engineering Education. During the training, teachers have the opportunity to not only develop CBL with EDP curricular Units that will be implemented during the school year but also work with the CEEMS project resource team. In CEEMS, an experienced resource team, consisting of three retired engineers and seven education specialists, takes on this role. While the whole 10 members of the resource team are collectively available to all the teachers, each teacher is assigned to two resource team coaches. Generally, one is an engineer and another is a seasoned educator. In addition, teachers in their first year of the program are assigned a third member of the team—a Fellow, an engineering doctoral student who has expressed an interest in pursuing an academic career upon graduation and has participated in a Preparing Future Faculty (PFF) program that includes a course on teaching and assessment methods, classroom dynamics, and all aspects of a future faculty career. The program builds on this course by also providing workshops to learn more about students learning, communication skills and teaching in an apprenticeship environment designed so that Fellows learn from educators (participating teachers) as the Fellows provide them support in engineering content, design practices and career choices.

This resource team support is also integral in curricular Unit development. The primary resource coach for each teacher “signs off” on each Unit prior to it being considered completed and ready for teaching. A standard template for a Unit and activity is made available to a teacher, which is used by the resource team coach to check compliance of completion of the required elements of a Unit prior to teaching. The same support team observes and provides assistance during the implementation of the Unit. The primary coach meets with the teacher after each Unit is complete to de-brief and discuss ways to improve the next Unit’s implementation. In addition to these professionals, the engineering Fellows trained in the pedagogies used in the project visit the teachers on a regular basis (10 hours per week, with one Fellow assigned to 4-6 teachers) to support them implementing their Units. After a Unit has been taught, a teacher adds pre- and post-test results, methods used to address misconceptions and differentiation when teaching the Unit, and reflections on what worked and what changes are recommended, if any. The final Unit template is again reviewed and approved by the primary resource coach. One member of the project team does the final checking of each Unit prior to web dissemination.

The CEEMS Program is led by an institution of higher education in partnership with 14 school districts. CEEMS works to meet the growing need for engineering-educated teachers who are
equipped to provide learners with opportunities to achieve the recently revised Ohio New Learning Standards (21st Century Learning Skills). To address this need, CEEMS offers professional development pathways to teacher preparedness. The vision for CEEMS is to establish a cadre of teachers, some new to the teaching profession and others well-experienced in the classroom, who will implement, through teaching and learning, the explicit authentic articulation of engineering with science and mathematics in 7-12 grade classrooms.

The goals of the CEEMS Program are to:
1. Improve 7-12 science and mathematics achievement to prepare for and increase interest in the college study of engineering or other STEM careers.
2. Develop mathematics and science teacher knowledge of engineering and the engineering design and challenge-based instruction process through explicit training and classroom implementation support.
3. Recruit engineering undergraduates as science or mathematics teachers through involvement in teaching experiences with younger college students in the schools and through a defined licensure program.
4. Recruit career changers to science or mathematics teaching.
5. Build a sustainable education licensure STEM degree-granting infrastructure to positively impact the entire region.

In the CEEMS Program CBL is the pedagogy taught to the teachers. CBL is an active learning environment that engages students to plan their own learning. It is a structured model for course content delivery with a foundation in earlier strategies, such as collaborative problem-based learning. CBL is different from project-based learning in that instead of presenting students with a problem to solve, CBL offers general concepts from which the students determine the challenges they will address. The teacher’s primary role shifts from dispensing information to guiding the construction of knowledge by his or her students around an initially ill-defined problem. Developed by Apple, Inc. CBL encourages student groups, under a teacher’s guidance, to solve real world issues using technology and a hands-on approach. Grounded in academic standards, students begin with a relevant “big idea,” which the students can readily relate to. Collaboratively, from a set of possible “essential questions,” they choose one essential question (the “challenge”) to address and then identify “guiding questions” that will guide their analysis of the challenge topic. These questions outline what the students think they need to know to formulate a viable solution to the challenge. This is where content knowledge requirements can be established. Student teams seek to find answers to the guiding questions by participating in a variety of learning activities, conducting research, learning new material (independently, in groups or as part of a teacher-led lesson), experimentation, interviewing, and exploring various avenues to assist in crafting the best solution for the challenge. The EDP guides and informs the solution of the challenge.

CBL activities offer many of the benefits of project-based learning, as they engage students in real-world problems and make them responsible for developing solutions. Using CBL, students have the satisfaction that comes from solving both the issue to be tackled and the solution they develop. As participants determine where a problem lies, how a solution might be affected, and how technology can be leveraged to accomplish a workable result, they learn the value of critical thinking and reflection.
The CEEMS Program, as mentioned above, has modified CBL process to incorporate the EDP to solve the challenge. The EDP is a series of steps that engineers follow to come up with a solution to a problem. Because there are constraints, trade-offs, and performance objectives there will typically be a variety of potential solutions. Thus, the EDP is an iterative process that requires the design’s revision and optimization. In the CEEMS Program teachers are taught to utilize the EDP shown in Figure 1 below. Using knowledge gained (through the guiding questions and activities) and knowledge experiences they bring with them to the class, student groups identify the best alternative and implement and defend their best unique solution using media and technologies that are most effective for their case as a culminating activity.

**Key Questions**

The CEEMS Program trains middle school and high school teachers in engineering design pedagogy used within a challenge based learning approach. Changes to teachers’ instructional practices are briefly discussed below and in more detail in another 2015 ASEE conference Paper Presentation (Factors That Support Teacher Shift to Engineering Design). The main focus of this paper is on the student outcomes associated with these changes in teaching practices. The key questions are: 1) When teachers shift from teacher-centered pedagogy to an engineering design- and challenge-based, student-centered approach, how are these changes perceived by students? 2) How do students communicate their understanding of the EDP? 3) How does this affect their attitudes related to learning?

**Figure 1: The Engineering Design Process Steps**

**Student Survey Development**

Student surveys are one method of evaluating the impact of EDP within the context of the CBL approach implemented in classrooms. During the first year of the project implementation, the Student Feedback Form, originally developed for administration at the end the CEEMS Unit, did not specifically address whether the EDP approach was being implemented with full integrity, as intended. For instance, did the students use the complete cycle (Identify & Define→ Gather
To answer some of these questions, the Evaluation and Project Team created new student surveys that included both open-ended and close-ended questions. Four teachers piloted the revised, more detailed instruments during and after the implementation of their third and final Unit during the 2012-2013 academic school year. Students completed surveys at three critical junctures: 1) Student Big Idea Survey: administered after the teacher guided the students from the big idea to the guiding questions; 2) Student Engineering Design Process Activity Survey: administered after the EDP activity; and 3) Student Post-Unit Survey: administered after the Unit was completed. The teachers who agreed to participate in the pilot did so voluntarily and represented diversity in grade level and subject level taught. Two were middle school (7th and 8th grade) teachers, one science and one mathematics, and the other two were high school teachers, once again one science and one mathematics.

Results from the pilot Student Engineering Design Process Survey, completed after the execution of the capstone EDP activity of the Unit, assessed the student’s perception of its connection to real life and the cyclic iterative engineering design steps of the EDP. Specifically, students were asked to draw or diagram the EDP; the steps were provided out of order and to answer how they acted like an engineer. These two questions were developed after consultation with STEM education researchers at the Boston Museum of Science, who developed the “Draw an Engineer” technique\textsuperscript{13, 30}. No student provided a near perfect picture of the EDP, although 31% (56/182) came close to getting the steps in order. Only 4% (8/184) articulated in pictures or in words the concept that engineering design was a cyclical process and only 16% (29/184) clearly indicated in their representations that EDP involved multiple iterations or re-testing. Part of the reason may be that teachers expose students to different versions of the EDP; in these alternate versions, the steps of the process are labeled differently. Also, student surveys can be perceived as extra work by students for which they receive no academic credit and, as a result, some students did not complete this section or simply numbered the steps (1, 2, 3, etc.) rather than drawing a representation of the process. The lack of accurate student representations may not indicate that they do not understand the EDP. In the CEEMS project, the teachers’ goal in implementing their Units is to deliver or reinforce content in an innovative way and to facilitate students’ educational experiences so that they become better problem solvers or critical thinkers. The end goal is not to have students memorize the EDP but to have students be able to use the EDP to identify, implement, test, redesign, retest solutions so that the most appropriate solution can be found.

After this pilot study, student surveys were revised and the students understanding of the EDP process via the drawing of the EDP cycle and the question about how the students acted like an engineer during this Unit were incorporated into one survey that was distributed at the end of the Unit. This change was done to minimize the time burden of completing two surveys for students and in practice, the EDP activity was taught toward the end of a Unit and the surveys were being administered after each other adding to survey fatigue among students. The revised surveys have been administered to the students in participating CEEMS teachers’ classes during the 2013-
2014 and 2014-2015 academic years. See Figure 2. The results discussed in this paper are from the 2013-2014 academic year since the Units are still be implemented during 2014-2015.

In 2013-2014, teachers returned 4,545 Student Feedback Surveys to the evaluation team. Of these returned surveys, there were 3,696 surveys that had all close-ended questions completed. Students’ completion of these surveys was voluntary and while all teachers allowed time for students to fully complete the survey after the Unit was completed, all students did not answer all close-ended questions. The question that was not answered the most was the first question rating the Unit overall, possibly because it was at the top of the survey and had a different scale compared to the other questions. For the current academic year, we have asked teachers to remind students to answer this question. A factor analysis was used to identify three constructs within the surveys: 1) Overall Feedback – included all questions; 2) Attitudes Related to Learning; and 3) Classroom Instructional Process. Since the first question, “Overall, I would rate this Unit as …” had a different scale and a lower completion rate it was not in the construct scale reliability analysis using Cronbach’s Alpha statistic. The scale used was: 4=strongly agree, 3=agree, 2=disagree, and 1=strongly disagree. The survey items, or questions, included in each construct and the Cronbach’s Alpha statistic for the scales and scale with the item deleted from the construct are shown in Table 1. When interpreting Cronbach’s Alpha, the closer the coefficient is to 1.0, the greater the internal consistency of the items in the scale. In other words, the scale is more likely to be measuring one construct of one or more factors but they are internally consistent. George and Mallory provide the following rules of thumb: “α > 0.9 – Excellent, α > 0.8 – Good, α > 0.7 – Acceptable, α > 0.6 – Questionable, α > 0.5 – Poor, and α < 1.5 – Unacceptable” (p.231).

For the overall feedback construct, the reliability of the entire survey was calculated and it was good, Cronbach’s Alpha = 0.884. Furthermore, when any item was removed from any scale considered for the overall feedback construct, it was ensured that either the reliability stays equivalent or goes down, indicating that all items (or questions) are adding value when computing the Cronbach’s Alpha values for this construct. For the second construct, which looks at attitudes related to learning and includes 7 items, the reliability was good, Cronbach’s Alpha = 0.804. Furthermore, when looking at individual items within this construct, they are all adding value as indicated by the “Cronbach's Alpha if Item Deleted” reliability scores. For the third construct, survey items that are related to the instructional practices used in the classroom, which include CBL (challenge based learning), EDP (engineering design process) and ACS (applications, careers and societal impacts) were grouped together. All Units developed by a teacher explicitly incorporate these three instructional strategies during the Unit development and entered in the Unit Template prepared and approved prior to teaching, which is revised and augmented to include student learning assessment results and teacher reflections after the Unit is taught. There are 10 items in this construct and the reliability is also good, Cronbach’s Alpha = 0.816, with all items adding value as described above. These results indicate that teachers are comfortable using these pedagogical techniques leading to a more consistent and effective teaching pedagogy. As stated previously, a summary of the Cronbach’s Alpha statistics for the constructs and the construct scale of each item is removed is in Table 1.

Additionally with regard to EDP instruction, the CEEMS project team has reviewed the results and has determined that the teachers may have been implementing different versions of the EDP
Figure 2: Revised Student Feedback Survey

CEEMS Student Feedback Survey

1. Please fill in the information in the box below:
   Name: [ ] Date: [ ] Grade: [ ] Period: [ ] Teacher: [ ]

2. In a drawing or Allegro, arrange the following words in the order of the steps you just used in the engineering design process activity and connect each with an arrow, with the arrow directed pointing to the activity that will come next. You can use any of these words more than once, if needed.
   a. Identify and Define
   b. Do: Again
   c. Communicate Solution(s)
   d. Evaluate or Test Solution(s)
   e. Refine
   f. Select Best Solution to Try
   g. Further Information

3. How did you act like an engineer during this unit? Please be specific.

4. What type of engineer did you act like?

(Survey continues on the back of this page.)

Thinking about the unit you just completed, please choose your level of agreement to the following:

1. Overall, I would rate this unit as...
   - Excellent
   - Good
   - Fair
   - Poor

2. I received guidance from my teacher when I asked for it.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

3. I learned a lot.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

4. This unit related to the real world.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

5. I understood how the engineering design process activity allowed us to use the guiding questions to solve the challenge selected.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

6. Solving this challenge can help others, our community, and society.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

7. I contributed to the group’s solution to the challenge.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

8. Listening to other student’s ideas was an important part of the unit.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

9. There are many solutions to this problem.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

10. We were able to test our initial solution.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

11. After our initial test, we were able to think about changes we wanted to make to have a better solution to the challenge.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

12. I like problems best when they really make me think.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

13. I am excited that we found a solution to this challenge.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

14. I participated more during this unit than I usually do in class.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

15. I had setting challenges as a more effective way to learn than the way we are usually taught.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

16. This unit made me more interested in Engineering.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

17. This unit made me feel more confident about math or science.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

18. I learned about the careers related to this challenge and our solution.
    - Strongly Agree
    - Agree
    - Neutral
    - Disagree
    - Strongly Disagree

19. If you want the teacher, list three changes that would make this unit better so that students learn more.

20. For summary purposes only, please indicate if you are a male or female.
    - Male
    - Female
process (i.e., the flow diagram presented in Figure 1). While all EDP models have similar steps and are cyclical, the exact wording of the steps and order are slightly different. These differences can lead to lower rubric scores since we developed our scoring rubric using the official EDP diagram used by the CEEMS project team during teacher professional development. In the future, all teachers will be asked to use the same EDP diagram as presented in Figure 1 in this paper. We expect the reliability of the construct to improve as the surveys administered during the current academic year are analyzed.

The open-ended questions on the first page of the Student Feedback Survey are directly related to students’ knowledge of the implementation of the EDP and the understanding of the tasks completed by engineers as they solve real-life problems and challenges. Rubric was developed to score these questions. A drawing rubric has been fully developed to score all drawings submitted in 2013-2014, which is briefly described in the section that follows. The tasks rubric is still under development and will be discussed at a later date.

**Rubric Development to Assess EDP Drawings**

As discussed previously, the EDP used in this program is the formulation of a plan to help an engineer build a product or formulate a process with a specified performance goal and is shared with the CEEMS teachers during their annual SIT professional development. EDP involves a number of steps, and parts of the process are repeated before a final product or solution is identified. Specifically, we observed the nature of students' misconceptions and the effects the CBL approach had on a conceptual understanding of EDP. On the first page of the Student Feedback Survey, students were asked to represent their understanding of EDP by arranging and connecting nine phrases given to them representing different aspects of EDP, as it is implemented in the CEEMS project as shown in Figure 1.

The rubric used to score the EDP student drawings was developed by a team of evaluators with education and engineering backgrounds using an iterative process over a five month time frame. The rubric development team consisted of two evaluators, one with an engineering degree and industry experience, one engineering education faculty, and one engineering doctoral student. The process used input from previous articles looking at EDP student assessments\(^1\,^2\,^6\).
<table>
<thead>
<tr>
<th>Survey Item</th>
<th>Items in Overall Feedback Construct</th>
<th>Cronbach’s Alpha for Scale with Select Items Deleted</th>
<th>Items in Attitudes Related to Learning Construct</th>
<th>Cronbach’s Alpha for Scale with Select Items Deleted</th>
<th>Items in Classroom Instructional Process Construct</th>
<th>Cronbach’s Alpha for Scale with Select Items Deleted</th>
</tr>
</thead>
<tbody>
<tr>
<td>I received guidance from my teacher when I asked for it.</td>
<td>X</td>
<td>0.879</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I learned a lot.</td>
<td>X</td>
<td>0.876</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This Unit is related to the real world.</td>
<td>X</td>
<td>0.879</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I understand how the engineering design process activity allowed us to use the guiding questions to solve the challenge selected.</td>
<td>X</td>
<td>0.876</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solving this challenge can help others, our community, and society.</td>
<td>X</td>
<td>0.877</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I contributed to the group's solution to the</td>
<td>X</td>
<td>0.879</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Listening to other student's ideas was an important part of the Unit.</td>
<td>X</td>
<td>0.880</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>There are many solutions to this problem.</td>
<td>X</td>
<td>0.880</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>We were able to test our initial solution.</td>
<td>X</td>
<td>0.879</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After our initial test, we were able to think about changes we wanted to make to have a better solution to the challenge.</td>
<td>X</td>
<td>0.878</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I like problems best when they really make me think.</td>
<td>X</td>
<td>0.879</td>
<td></td>
<td></td>
<td></td>
<td>0.782</td>
</tr>
<tr>
<td>I am excited that we found a solution to this challenge.</td>
<td>X</td>
<td>0.873</td>
<td></td>
<td></td>
<td></td>
<td>0.769</td>
</tr>
<tr>
<td>I participated more during this Unit than I usually do in</td>
<td>X</td>
<td>0.882</td>
<td></td>
<td></td>
<td></td>
<td>0.803</td>
</tr>
<tr>
<td>I feel using challenges is a more effective way to learn than the way we are usually taught.</td>
<td>X</td>
<td>0.876</td>
<td></td>
<td></td>
<td></td>
<td>0.778</td>
</tr>
<tr>
<td>This Unit made me feel more interested in</td>
<td>X</td>
<td>0.877</td>
<td></td>
<td></td>
<td></td>
<td>0.767</td>
</tr>
<tr>
<td>This Unit made me feel more confident about math or science.</td>
<td>X</td>
<td>0.874</td>
<td></td>
<td></td>
<td></td>
<td>0.762</td>
</tr>
<tr>
<td>I learned about the careers related to this challenge and our solution.</td>
<td>X</td>
<td>0.877</td>
<td></td>
<td></td>
<td></td>
<td>0.806</td>
</tr>
</tbody>
</table>
The initial scoring rubric included a five-point scale (0-4) with the scores increasing as students included higher number important elements of EDP. These elements were defined as: 1) Correct terms are used; 2) Terms are correctly connected to each other; 3) Cyclical representation of EDP; and 4) Terms are connected to each other in the correct order. Two scorers were assigned to student drawings from three teachers (approximately 10% of the total number of drawings). Then, the scorers met and discussed their experience using this rubric. It was determined that the initial scoring rubric did not have enough detail to truly discriminate between low quality and high quality drawings since all elements of EDP identified were not equivalent in importance. The second revised rubric assigned relative importance to the different steps of the EDP shown in Figure 1 leading to higher rubric scores. But, as it was being used, the inter-rater reliability was calculated and it was found to be very low (approximately 0.4), because the rubric was open to too much interpretation relative to correct order of EDP steps, how a student can represent connections of the EDP steps, and student’s interpretation of a complete design cycle and repetition of the design cycle. After a total of seven iterations of the rubric, the scorers developed a robust definition for each score that was fully understood by all. The final rubric formulated by the team is presented as Table 2. The four-person team of trained scorers used the final rubric to score 4,300 EDP drawings from all 34 teachers (100%) received during the 2013-2014 academic year. Two trained scorers used the final rubric to rate each drawing. If there was a difference in scores, a third scorer reviewed the drawing and their score was the final score used for the drawing.

For this multiple person scoring team, we calculated our inter-rater reliability to evaluate this newly developed instrument, scoring rubric, for accuracy and base construct validity. We evaluated multiple raters’ scores to ensure that they were uniformly coding their observations in accordance with pre-defined operational definition of EDP, the construct measured. By showing some amount of inter-rater reliability in identifying points along the continuum of the construct, researchers show objective evidence for the very existence of the construct28. After full training and discussions described above, inter-rater reliability was excellent with Cronbach’s Alpha statistics equaling 0.935 to 0.983 for rater pairs (raters 1 & 2; raters 1 & 3, and raters 1 & 4)9,10.

**Student Impacts**

Implementation of teacher Units is impacting the students’ content knowledge as well as their ability to solve problems, work in a group, and participate and engage in class activities. These findings will be reported in a separate paper. In addition, students are becoming aware of the CBL and EDP processes and how they can be used to solve real world problems. The impact the Units have on students’ EDP knowledge and its effects on learning is evidenced by: the students’ attitudes related to their learnings from the lessons; and the teachers’ impressions of student learning, experiences and attitudes as reported through teacher surveys and end-of-year teacher focus groups. The highlights of these findings are reported in this section. A few examples cited by the teachers’ reporting impact on students are presented below:

*Higher student engagement and the challenges also provided a healthy academic competition that some students really thrived on.*

*Overall learning is higher, covering all kinds. Students are more likely to take academic risks and think better on their own.*
Students’ learning curve increased greatly compared to the way I used to teach. Students work together and implement things.

With usual lessons, wrong is wrong. With the engineering design process, failure is actually a good thing. They [students] learn something that didn’t work so they can go back and redesign.

Table 2: EDP Drawing Rubric Scoring Definition Progression

<table>
<thead>
<tr>
<th>Rubric #</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Student has no drawing OR has included the EDP elements incorrectly.</td>
<td>Student has represented one element of EDP correctly (from list of 4 elements).</td>
<td>Student has represented two elements of EDP correctly (from list of 4 elements).</td>
<td>Student has represented three elements of EDP correctly (from list of 4 elements).</td>
<td>Student has represented all elements of EDP correctly (from list of 4 elements).</td>
</tr>
<tr>
<td>2-3</td>
<td>Student has no drawing OR has included the EDP terms in an incorrect order.</td>
<td>Student has included, listed, the terms of EDP in the correct order.</td>
<td>Student has connected these terms to each other in the correct order but it is in a linear progression.</td>
<td>Student connected these terms to each other in a correct cyclical representation.</td>
<td>Student has a correct cyclical representation and has indicated that the cycle needs to be repeated.</td>
</tr>
<tr>
<td>4</td>
<td>Student has no relevant drawing</td>
<td>Student uses correct terms OR Terms are connected to each other</td>
<td>Student uses correct terms AND Terms are connected to each other</td>
<td>Student uses correct terms AND Terms are connected to each other AND Cyclical with repetition</td>
<td>Student uses correct terms AND Terms are connected to each other AND Cyclical with repetition AND Terms are in the correct order</td>
</tr>
<tr>
<td>5</td>
<td>Student has no relevant drawing OR Less than 6 terms written</td>
<td>Student uses at least 6 correct terms OR Terms are connected to each other but not rewritten in the space (numbers or arrows by the typed words)</td>
<td>Student uses at least 6 correct terms AND Terms are connected to each other either by numbers or arrows</td>
<td>Student uses at least 8 correct terms AND Terms are connected to each other AND Cyclical with repetition (actually connected with arrows in circles; the words “do again” by themselves does not imply cyclical)</td>
<td>Student uses at least 8 correct terms AND Terms are connected to each other AND Cyclical with repetition AND Terms are in the correct order</td>
</tr>
<tr>
<td>6</td>
<td>SAME AS ABOVE</td>
<td>ADDED Connected by Lines also</td>
<td>ADDED Connected by Lines also</td>
<td>SAME AS ABOVE</td>
<td>DIFFERENT ACCEPTABLE ORDERS BELOW **</td>
</tr>
<tr>
<td>7</td>
<td>SAME AS ABOVE</td>
<td>SAME AS ABOVE</td>
<td>SAME AS ABOVE</td>
<td>SAME AS ABOVE</td>
<td>DIFFERENT ACCEPTABLE ORDERS BELOW ***</td>
</tr>
</tbody>
</table>

Acceptable orders for version 5:
1. Identify and Define
2. Gather Information
3. Identify Alternatives
4. Select Best Solution
5. Implement Solution
6. Evaluate Solution
7. Communicate Solution
8. Refine
9. Do Again
1. Identify and Define
2. Gather Information
3. Identify Alternatives
4. Select Best Solution
5. Implement Solution
6. Evaluate Solution
7. Refine
8. Do Again
9. Identify and Define
2. Gather Information
3. Identify Alternatives
4. Evaluate Solution
5. Select Best Solution
6. Implement Solution
7. Refine
8. Communicate Solution
9. Do Again

**Acceptable order for version 6:
- Both “Identify and Define” and “Gather Information” need to be stated as 1 and 2 but the order does not matter.
- “Communicate” can be any where
- Middle items are “Identify Alternatives”, “Select Best Solution” and “Evaluate Solutions”
- 2 of the last three items need to include “Refine”, “Implement Solutions” or “Do Again”

*** Acceptable order for version 7:
- Both “Identify and Define” and “Gather Information” need to be stated as 1 and 2 but the order does not matter.
- “Communicate” can be any where
- Middle items are “Identify Alternatives”, “Select Best Solution” and “Evaluate Solutions”
- 2 of the last three items need to include “Refine/Do Again”, “Implement Solutions” or “Evaluate Solution
Rubric scores from students’ EDP drawings are presented in Table 3. For all students, the EDP scoring results indicate that the most frequent score given to 47.8% of the drawings was a “2” (‘Student uses at least six correct terms out of the nine terms listed’ AND ‘Terms are connected to each other’). An encouraging finding was that 9.6% of the students received the highest score, indicating that they can represent via a drawing all aspects of the EDP cycle used as part of the CEEMS project. Showing the need for improvement was the fact that almost one out of every five surveys (19.1%) was left blank or did not use at least six terms given to represent the EDP cycle. In summary, these results indicate that the majority of students taught with CEEMS Units were able to identify the steps in the EDP process and to understand that they are connected. However, they were not able to represent the cyclical nature of EDP in the correct order of the steps. Since these results are a reflection of teachers’ Unit implementations, we will work with the project team and resource team to support professional development for the teachers to improve their CBL and EDP instruction. For reference, Figure 3 has an example of an EDP drawing that scored a 4 using this rubric.

**Table 3: Rubric Scores from Students’ EDP Drawings: 2013-2014 Academic Year**

<table>
<thead>
<tr>
<th>Rubric Score</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Classes</td>
<td>822</td>
<td>761</td>
<td>2027</td>
<td>248</td>
<td>412</td>
</tr>
<tr>
<td>(n=4300)</td>
<td>(19.1%)</td>
<td>(17.7%)</td>
<td>(47.8%)</td>
<td>(5.7%)</td>
<td>(9.6%)</td>
</tr>
</tbody>
</table>

In a drawing or diagram, arrange the following words in the order of the steps you just used in the engineering design process activity and connect each with an arrow, with the arrow-head pointing to the activity that will come next. You can use any of these words more than once, if needed.

- Identify and Define
- Do Again
- Communicate Solution(s)
- Evaluate or Test Solution(s)
- Select Best Solution to Try
- Identify Alternative(s)
- Refine
- Gather Information
- Implement Solution(s)

**Figure 3: EDP Drawing with a Rubric Score of 4**

Additional support for the positive impact of the CBL and EDP Units can be found by looking at the several questions in the Student Feedback Survey pertaining to attitudes related to learning.
The questions were asked using a 4 point scale with 4=strongly agree, 3=agree, 2=“disagree” and 1=strongly disagree. Specific to our scale, a mean value of 3 or more is desired since that means the respondents, as a group, agreed or strongly agreed with the positive statements in the survey. The standard deviation of a scale indicates the dispersion of the scores compared to the mean. Its absolute value is not good or bad, especially if you want people to have high scores, like we do in this survey. Overall, students reported positive attitudes related to learning (all means were greater than 2.8 out of 4 with a standard deviation between 0.652 and 0.943) on these related student survey statements. The responses with the highest means were “I learned a lot” (mean of 3.23 out of 4 with a standard deviation of 0.652), “I am excited that we found a solution to this challenge” (mean of 3.14 out of 4 with a standard deviation of 0.760), and “I feel using challenges is a more effective way to learn than the way we are usually taught” (mean of 3.16 out of 4 with a standard deviation of 0.750). The ratings of specific items are summarized in Table 4.

Table 4: “Student Feedback” – Student Survey Responses

<table>
<thead>
<tr>
<th>Item</th>
<th>N</th>
<th>Mean*</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I learned a lot.</td>
<td>4426</td>
<td>3.23</td>
<td>0.652</td>
</tr>
<tr>
<td>I like problems best when they really make me think.</td>
<td>4392</td>
<td>2.86</td>
<td>0.882</td>
</tr>
<tr>
<td>I am excited that we found a solution to this challenge.</td>
<td>4382</td>
<td>3.14</td>
<td>0.760</td>
</tr>
<tr>
<td>I participated more during this Unit than I usually do in class.</td>
<td>4372</td>
<td>2.97</td>
<td>0.846</td>
</tr>
<tr>
<td>I feel using challenges is a more effective way to learn than the way we are usually taught.</td>
<td>4384</td>
<td>3.16</td>
<td>0.750</td>
</tr>
<tr>
<td>This Unit made me feel more interested in Engineering</td>
<td>4405</td>
<td>2.79</td>
<td>0.943</td>
</tr>
<tr>
<td>This Unit made me feel more confident about math or science.</td>
<td>4397</td>
<td>2.86</td>
<td>0.851</td>
</tr>
</tbody>
</table>

* Scale: 4=Strongly Agree; 3=Agree; 2=Disagree; 1=Strongly Disagree

In addition to the students’ attitudes toward their learning, their teachers also observed positive changes in student behavior. When thinking about the entire Unit implementation, both cohorts had the highest agreement level for the same statement on the teacher post-Unit survey, “Overall engagement of my students increased during this Unit compared to non-CBL Units” (means of 3.66 and 3.51 out of 4, respectively, for Cohort 1 and Cohort 2). An area for concern was identified by the teachers in their responses to various statements related to student outcomes when they completed the post-Unit survey. In particular, the statement with the lowest agreement level for both cohorts indicated that a number of teachers did not think that “students mastered the expected material” (mean of 3.17 out of 4 for Cohort 1 and mean of 2.91 out of 4 for Cohort 2). Survey results are summarized in Table 5. These sentiments were also expressed during the focus groups. Teachers felt that student engagement was very high for these Units compared to more typical Units they taught and this was especially true for students who typically might be more academically challenged. During the focus group, teachers suggested
teaching the content prior to the Unit and subsequently reinforcing it as part of the CBL and EDP processes.

Table 5: “Post-Survey Questions Related to Student Outcomes” – Teacher Survey

<table>
<thead>
<tr>
<th>Item</th>
<th>All Units</th>
<th>N</th>
<th>Mean*</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>My students mastered the expected material.</td>
<td>86</td>
<td>3.00</td>
<td>.669</td>
<td></td>
</tr>
<tr>
<td>Overall engagement of my students increased during this Unit</td>
<td>86</td>
<td>3.56</td>
<td>.566</td>
<td></td>
</tr>
<tr>
<td>My students worked effectively in teams during this Unit.</td>
<td>85</td>
<td>3.24</td>
<td>.630</td>
<td></td>
</tr>
<tr>
<td>My students demonstrated flexibility and adaptability.</td>
<td>86</td>
<td>3.41</td>
<td>.582</td>
<td></td>
</tr>
<tr>
<td>My students showed leadership.</td>
<td>85</td>
<td>3.34</td>
<td>.524</td>
<td></td>
</tr>
<tr>
<td>My students assumed responsibility for getting to a solution.</td>
<td>85</td>
<td>3.42</td>
<td>.624</td>
<td></td>
</tr>
<tr>
<td>My students effectively presented their solution to others.</td>
<td>86</td>
<td>3.27</td>
<td>.640</td>
<td></td>
</tr>
</tbody>
</table>

* Scale: 4=Strongly Agree; 3=Agree; 2=Disagree; 1=Strongly Disagree

In summary, teachers noted that the CBL and EDP Units had positive effects on student outcomes, student attitudes, and student knowledge. The following teacher quotes demonstrate teacher perceptions regarding positive student outcomes:

*Give students more directives on how to even successfully complete an activity, more forward instructions. But still had plenty of opportunities to make decisions do construction of things, and it did not take away from the challenge base in any way.*

*Collaboration, Communication, Creativity, Critical Thinking – these did all four.*

Conclusions and Recommendations for Future Study

Students reported that they learned from the CEEMS Units and rated them highly. The majority of the students depicted the EDP with correct terms in the correct order, but did not include the cyclical and repeat elements. The project team members will emphasize these aspects of EDP during Unit development and implementation in the future.

More studies are needed to compare student performance using engineering design challenges versus a more teacher-directed approach. As the state of Ohio moves to more performance-based assessment starting the 2014-2015 school year, this comparison will become even more relevant. In order to sustain the program, the project team will need to pinpoint exact factors and degree of treatment needed to change teachers’ instructional practices. For example, as the grant expires and the project team examines ways to sustain the efforts, could a smaller scale teacher training program be developed that yields the same degree of effectiveness?
Acknowledgement

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Bibliography


