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This material is based on work supported by the National Science Foundation Under Grant No. ESI-0426421

PLTW and Epics-High: Curriculum Comparisons to Support Problem Solving in the Context of Engineering Design

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Executive Summary

A comparative study was conducted to compare two approaches to engineering design curriculum between different schools (inter-school) and between two curricular approaches, *Project Lead the Way* (PLTW) and *Engineering Projects in Community Service* (EPIC High) (inter-curricular). The researchers collected curriculum materials, including handouts, lesson plans, guides, presentation files, design descriptions, problem statements, and support guides. The researchers conducted observations in the classrooms to collect qualitative indicators of engineering/technology reasoning, collect data on the nature of students' questions, how students define problems, and operate within the constraints of a design problem.

Observational studies were conducted with students participating in *Project Lead the Way* and with students participating in *Engineering Projects in Community Service* (EPICS). Study participants were asked to work through an ill-defined problem, in this case the problem of creating a new playground for an elementary school. The data from these protocols were analyzed using a coding process; a list of universal technical mental processes (Halfin, 1973) and a computer program OPTEMP (Hill, 1997) to record frequency and time of each mental process employed by the students. The data were used to identify common cognitive strategies employed by the students and to determine where students placed greatest emphasis during the observation period.

General findings indicated that participants in the *EPICS-High* program were in general more solution-driven problem solvers, while the *Project Lead the Way* participants were generally problem-driven as defined by Kruger & Cross (2006). Although the participants in both groups had completed advanced courses in mathematics; mathematics was rarely employed (less than 3%) to describe constraints of the problem or predict results of proposed solutions. Over half of the students became fixated at some point on the provided picture. (Smith, Ward, & Schumacher, 1993). This study provides important insight about how students solve ill-defined problems, providing vital information for technology education as it seeks to implement engineering design.

This research was conducted through support of National Science Foundation under Grant No. ESI-0426421

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Introduction

The purpose of this study was to better understand the current status of engineering-focused curriculum programs at the high school level and its greater impact on student learning. Specifically, this study examined the implementation of Project Lead The Way and EPICS High, engineering-focused curriculum and its impact on students' abilities to employ the engineering design processes using mathematical and scientific reasoning to solve engineering design problems; a construct of interest to K-12 engineering education and the greater STEM community.

The rise in engagement of secondary engineering education (Douglas, Iversen, & Kalyandurg, 2004) and the increase in development of engineering-focused curriculum for grades 9-12 (Dearing & Daugherty, 2004) provide strong rationale for examining pre-existing secondary engineering-focused programs to evaluate the impact on student learning.

Background

No Child Left Behind (NCLB) legislation generated a new age of accountability by placing emphasis on improving students' achievement in the core subjects. Recent trends in secondary education have generated multiple efforts to integrate core subjects such as math and science with technology education. Researchers in technology education have investigated the effects of technology education instruction on performance in mathematics and science for over a decade (Childress, 1996; Merrill, 2001). Research indicates that engineering drawing and design courses have had a significant impact on student achievement on mathematics standardized end-of-year tests (Dyer, Reed, & Berry, 2006). Another study discovered that engineering design instruction at the middle school level reduced the performance gaps among certain ethnic groups and increase student's conceptual knowledge of science, while simultaneously generating higher order thinking skills such as analysis and synthesis (Cantrell, Pekcan, Itani, &Velasquez-Bryant, 2006). Each of these studies indicate that there is a growing interest in investigating how engineering-focused instruction impacts student learning.

In addition, several initiatives have started in the last decade to introduce engineering principles and engineering reasoning into grade 9-12 classrooms (Brophy, Klein, Portsmore, & Rogers, 2000). While PLTW and other curriculum programs like EPICS-High focus on different aspects, from engineering problem solving to service learning; each of these new curriculums share the lack of a cohesive body of systematic and rigorous research studies investigating the effectiveness of their programmatic efforts. Specifically, there is a lack of investigation on higher order thinking, open-ended problem solving and the development of design and engineering knowledge/skills (Chaker, 2008).

Dyer, Reed, and Berry (2006) recommended more research on the instruction of engineering design to accurately determine what elements of instruction are most beneficial to student's learning of math and science. Similarly, Sheppard, Pellegrino, & Olds (2008) and Brophy (2008) call for more research on engineering efforts in high schools. This becomes especially pressing, since individual states develop specific engineering standards (i.e. Massachusetts) and specific teacher licensures will likely follow. As these programs continue to grow, there is a need to build a strong base of rigorous research to provide educated and specific feedback on how to improve existing curricula and build a cohesive research agenda on engineering reasoning development in the K-12 grade spectrum.

Participants

Project Lead The Way (PLTW) is a national pre-engineering program that has been implemented into a number of high school and middle schools. The Project Lead The Way program launched in 1997 based on previous work in the 1980s by Richard Blais at Shenendehowa Central School (Blais & Adelson, 1998). Project Lead The Way has grown to serve over 1300 schools and 175,000 students (Bottoms & Anthony, 2005). Over 280 high schools in the state of Indiana alone are currently implementing Project Lead The Way. Two PLTW schools in northwestern Indiana were selected for this study because they had successfully implemented PLTW at the high school level and had similar student demographics.

Engineering Projects in Community Service (EPICS) is a national engineering-centered, academic service-learning program initiated at Purdue University (Coyle, Jamieson, & Oakes, 2005). The main tenets of service learning are 1) curricular connections; 2) reflection, 3) community partnerships, 4) authentic, complex and ill-structured problems, 5) addressing real needs, and 6) performance-based assessment (Honnet & Poulsen, 1989). Multidisciplinary teams are formed with local not-for-profit organizations to define, design, build, test, deploy, and support engineering-centered projects that significantly improve the organization's ability to serve the community. EPICS-High (for grades 9-12) began in 2007, with the aim of bringing the engineering design concept into the high school environment. The program has quickly grown to 32 active high schools across the nation with over 650 students served, 50% female students, 48% minority students, and over 50% in free and reduced lunch programs. Two EPICS-High programs in northwestern Indiana were chosen for their record of success in implementing the EPICS-High program. Every effort was made to select participating schools that align with the student body demographics.

Table 1. Participating School General Student Demographics

	PLTW 1	PLTW 2	EPICS 1	EPICS 2
Enrollment	883	1606	1833	883
Graduation Rate	75.7%	92.2%	83.8%	75.7%
White	72%	88%	86%	72%
Hispanic	25%	5%	7%	25%
Multicultural	2%	3%	2%	2%
Asian	1%	2%	1%	1%
Black	1%	2%	3%	1%
Native American	1%	0%	1%	1%
Surrounding Area	Rural	Urban Fringe	Urban Fringe	Rural

Research Questions

This study was guided by the following research questions. Since the nature of our research is comparative, the responses to each of the questions will be compared across different schools (inter-school) and across curricula (inter-curricula):

1. What are important elements embedded within an appropriate engineering design problem for high school students to study/solve?
2. What elements in the engineering design problems (or in the curriculum unit) encourage teachers to engage mathematical and science curricula elements and support mathematical reasoning or scientific reasoning of their students?
3. What are the most common elements within student dialogues as they define engineering, engage in student collaboration and class discussions when seeking to solve engineering design problems? Which attributes or elements of engineering are missing or strongly represented?
4. What are common cognitive and meta-cognitive strategies employed by high school students as they work to solve an engineering design focused problem?

Methodology

The research team collected curriculum materials from the participating classrooms, including textbooks, handouts, lesson plans, Power Point files, design descriptions, problem statements, and support guides. The researchers conducted observations in the classrooms to obtain qualitative indicators of engineering/technology reasoning and to collect data on the nature of students' questions, how students define problems, and how they operate within the constraints of an engineering design problem.

Next, a protocol analysis session was conducted with a group of three student volunteers from each site. Each volunteer was given the same design problem (the transfer problem) shown in Appendix B. Each student was asked how they would proceed from the given problem statement in order to improve the current condition described in the statement. See Appendix A for the complete protocol. The students were asked to define the problem, list all constraints that they impose on the problem, and describe how they would proceed to solve the problem. The participants were asked to verbalize their thoughts as they worked through the ill-defined problem (verbal protocol methodology). The researchers prompted participants to keep talking through the problem. The testing sessions were limited to thirty minutes, but most lasted between ten and fifteen minutes. Certainly, in the time constraints imposed by the testing session, a student would be unlikely to reach the final stages of the design process. However, one of the most important stages of the engineering design process, framing the problem, occurs early in the process of solving a technical problem. Experts in the field of design report that framing the problem is a critical step to the design process which occurs as soon as the designer is presented with a technical problem (Dym, Agogino, Eris, Frey, & Leifer, 2005; SchÖn, 1983). The transfer problem was developed to share characteristics of an ill-defined, complex, and dynamic design problem (Jonassen, 2000).

Analysis

The project involves two separate analyses of artifacts, (1) curriculum materials, and (2) results from selected students transfer problem analysis. Both forms of data were analyzed with an analytical induction framework (Bogdan & Biklen, 1992) similar to the constant comparative method of grounded theory (Strauss & Corbin, 1990), combining data analysis, further literature review, and theory-building in a cyclical manner. In the analytical induction approach, data built the basis for further descriptions and interpretations, and in contrast to grounded theory is informed by prior research.

As students progressed through the transfer problem session, the students' cognitive processes were identified and coded from a list of 17 universal mental processes (Halfin (1973). A computer analysis tool called the Observation Procedure for Technology Education Mental Processes (OPTEMP) (Hill, 1997) was utilized to capture, record, and organize the codes from each transfer problem session. The researchers coded the actions and cognitive processes used by each student participant as he or she worked through the engineering design problem.

Triangulation

Ary, Jacobs, Razavieh, and Sroensen (2006) indicate that collecting data from different sources and comparing these data sources is a good way to determine validity within a study. This comparison of multiple sources is called triangulation. Triangulation is a generally accepted research method to ensure validity. As multiple sources point to the same conclusions, the researcher can be relatively confidence that the researcher's instruments are measuring what they are intended to measure appropriately. For the purpose of this study, triangulation was achieved through the use of: classroom observation, transfer problem results, review of curriculum material, and student / teacher surveys. Through multiple sources of data, the researchers were able to achieve validation by triangulating these findings.

Limitations

The researchers acknowledge that the study has a small *n* of approximately 60 students observed in PLTW and EPICS High classes and an *n* of 12 participants for the observational protocol, therefore, the results of the study are not generalizable to all secondary engineering design programs.

Other possible limitations include a potential bias regarding PLTW and EPICS High. According to Merriam (1998) researchers must acknowledge potential biases within the final report of the study. The researchers acknowledge that a potential bias could exist regarding both PLTW and EPICS high due to the fact that the researchers work within an engineering/ technology teacher preparation program that provides undergraduate students with certification in PLTW courses and the fact that EPICS High was created by Purdue engineering education faculty. To help ensure that such biases did not taint research findings, the researchers implemented methods such as Merriam's observational elements guide, see appendix C. The observational elements guide provided researcher with guiding questions that required reflection on a variety of factors in order to maintain an objective perspective as the research collected observational data. The researchers also use triangulation methods to provide multiple perspectives and multiple forms of data. Finally, researchers used multiple raters on the observational protocol transfer problem session to maintain consistent and reliable data collection. These are sound research methodologies that can help to ensure an objective data collection process.

Findings

Classroom Observations:

A total of three class observations were conducted at each PLTW and EPICS-High site. Each PLTW and EPICS High class session was 90 minutes for a total of 270 minutes of observation at each site.

Project Lead the Way Observations

The course observed was PLTW *Principles of Engineering*. The PLTW students were working on marble sorting activity during the observation sessions, the activity required student teams to design and build a device to sort marbles by color using Fishertechnik parts. An observational template was used (Merriam, 2001); see Appendix C. The nature of much of the classroom dialogs were regarding Fishertechnik parts (motors, sensors, structures, etc) and how the students were planning to connect the various parts to make the device function properly. However, as the team devices began to be tested, malfunctions often occurred. As a result of these device malfunctions; students worked as cohesive teams to troubleshoot various problems encountered. Student dialogs were healthy problem solving conversations and represented cooperative team efforts. However, students did not appear to be using a systematic approach to solve problems. The students approach to solving problems was reactive as they employed trial and error approaches, which might also be described as “tinkering”. Students often were observed reconfiguring the device parts such as wires, motors, and sensors. Another example of the PLTW students limited systematic approach to solving problems through the design process was observed when one student voiced his concern to his instructor about being ill-prepared for the transfer problem session because he could not remember the order of the 12-steps engineering design process. Although, there is much more to engaging in the engineering design process then learning a list of steps within a design process, this observation may indicate the student’s lacked an understanding in how to use the engineering design process as a systematic approach to solving problems.

EPICS High Observations

Both EPICS High participating schools were observed for a total of three class observations. One important observation about both EPICS High classes was the use of an engineer’s notebook. Both Epics High programs required students to obtain and keep an engineer’s notebook for the course. The EPICS High School #1 class was discussing “great teams” during one of the classroom observations and “community” during another class observation. The community discussion was an EPICS High created lesson titled Your community…My community. The instructor led a class discuss by asking questions like “How big is your community?, Where does it begin and end?” The instructor encouraged students to think about how they individually define community, what did community mean to them. Later in the class, the discussion led to the brainstorming possible community service projects to be explored by the class. One researcher had a conversation with the EPICS #1 instructor who shared that his school started the EPICS High program to purposefully target the middle level academically performing students instead of targeting the high performing students. The course gave students an alternative to PLTW which the school also offers. The Purdue EPICS program provided a 48,000 dollar grant to provide the EPICS school #1 with new laptops for all the students to use in the class. The grant also allowed the school to travel to Aurora, IL to the Walter Payton Brew House roundhouse. Last year's EPICS High project was a feasibility study to restore the train roundhouse that is located in the community. EPICS High school #1 class is 12 weeks long.

One classroom observation at EPICS High #2 school found small groups of students (two groups of two students) discussing with the instructor their EPICS High community projects. The instructor reminded the students that they needed to be recording their design thinking in the design notebooks and how the information was to be recorded. The instructor asked the students to present their design project ideas informally to the group. One group selected a community project to design and build a walking path for students on school grounds, the path would need to be wheelchair accessible. The design team was talking about making a pathway using some sort of gravel. The design discussion lead to brainstorming the different material they could use so the wheel chairs won't get caught. The other design team selected a project to create a storage container that would allow teachers to use a magnetic key fob to lock and unlock their laptop computers in a storage unit. Many teachers at this school have complained about having to carry their laptops everywhere they go for security reasons instead of being able to just leave it in their classrooms or one central location. The EPICS High #2 class was small and as a result was a very informal classroom structure, however there was good classroom dialogue regarding the design process. The instructor emphasized the importance of creating a clear and concise problem statement and recording design work in the engineer's notebook. The EPICS High #2 instructor was new to the EPICS High program and had just completed EPICS training in the summer of 2009. The EPICS High #2 school program runs the EPICS High course as a club and not an official class; students do not get course credit and meet after school hours.

Curriculum Documents

A review of PLTW curriculum documents for the course *Principles of Engineering* revealed a focus on teaching students about systems, subsystems, open and closed loop systems, basic computer programming, and troubleshooting problems within a system. Later in the semester, students also learned about basic statics and dynamics. Furthermore, students were taught how to use free body diagrams and conduct basic vector analysis. This knowledge would have been helpful for student who participated in the transfer problem. However, this instruction came after the transfer problem testing session. Upon review of the *Principles of Engineering* curriculum, the researchers identify that the students are exposed to a limited scope of the engineering design process. PLTW curriculum program consists of a series of courses in pre-engineering; therefore it is unfair to fully assess students design capabilities upon their completion of just one course. Assessment of students who have experienced all the PLTW courses would be ideal such as in the PLTW capstone course: *Engineering Design and Development* (EDD). This course was studied in a similar protocol analysis study (Kelley, 2008). However, the schools in this study did not offer this course. Furthermore, most of the students used in this study had taken *Introduction to Engineering Design* that provided a broader overview of the engineering design process so students should have been prepared to employ the engineering design process to solve the transfer problem.

The EPIC High curriculum documents that were studied were lesson plan documents taken from EPICS High Curriculum Module 1- Design, week 3. The activities in this module focus on design notebooks. One activity required students to assess their current note-taking skills by examining their notebooks they keep for other classes. The activity asks students to brainstorm in a small group how the design notebook differs from traditional class notebooks.

Other similar class activities included making use of other people's design notes, building note taking skills, and building organizing skills for design notebooks. Lessons for later in the course focused on the topic of solving engineering problems in teams. These lessons required students get into small or large design teams and work to solve some ill-defined problems. One problem was as follows:

> In your group, solve the following design problem:
> Landfill space is rapidly running out. Develop a plan to eliminate your city's dependence on the local landfill. Imagine, for now, that the city's population is 100,000. As you solve this problem, each member should take notes according to your design notebook guidelines." (*EPICS High curriculum Module 1- Design lesson plans*, p.29).

When students were finished exploring possible solutions, they were required to compile a design record providing a design rational including experimental measurements, sketches, safety precautions, design criterion rational. Students were also asked to consider assessing how they functioned as a design team during the assignment. This exercise in open-ending problem solving would provide ideal experiences for students and should prepare students for the transfer problem. See Appendix B.

Ill-defined Transfer Problem Session:

Table 2. Transfer Problem Participants' Coursework

Participant	Grade level	Math courses	Science Courses	Technology Courses
PLTW 1	10	A1, G	ICP	AutoCAD, POE
PLTW 2	10	A1, A2	Biology, Physics	IED, POE
PLTW 3	10	A1, A2, G	Bio, Chem	IED, POE
PLTW 4	10	G, A-AP		IED, POE
PLTW 5	12	G, A2, T, PC, C		IED, POE, Bio-Tech
PLTW 6	11	G 1, G2, A3-A4, T, PC	Bio, Chem, Phys	IED, Design
EPICS 1	10	A1, G	Bio, ICP	EPICS, IED
EPICS 2	12	A1	Bio, Zoology, ICP	EPICS, Manufacturing, Communications, Construction, Robotics, Machining
EPICS 3	12	A2, G, PC, S	Bio, Chem	IED, EPICS
EPICS 4	12	A1, A2, G, PC, C	Bio, Chem, Phy, AP Phy	IED, POE, EPICS
EPICS 5	12	A1, A2, G, PC, C	Bio, Chem, Phy, Chem2	Manufacturing, Transportation
EPICS 6	12	A1, A2, G, PC,C	Bio, Chem, Phy, Chem2	EPICS

Math Courses Key: A1-Algebra; A2- Algebra II; G- Geometry; S- Statistics; T- trigonometry; PC- pre-calculus; C- calculus. **Science Course Key**: Ana- anatomy; Bio- Biology; Chem- Chemistry; ICP- Integrated chemistry and Physics; Phy- Physics. **PLTW Course Key**- IED- Introduction to Engineering Design; POE- Principles of Engineering

Project Lead The Way Transfer Problem Results

There were several similarities in the Project Lead The Way participant groups when comparing their employed cognitive processes during the protocol session. Out of the seventeen cognitive processes that were first identified by Halfin (1973), the participants only used eight of the seventeen processes. See Table 3. Due to testing session constraints such as time limits, location, available resources it was expected that cognitive processes such as *models/prototypes*, *measures*, and *testing* as well as other cognitive processes would not be used when developing a design solution. On average the PLTW students used the *analysis* (AN) cognitive process 37.6 % of the time with a range of low 18% to a high of 61%. The *design* (DE) cognitive process was used 36.5% of the time with a low 21% and a high of 53% of the time. These were the two most employed cognitive processes by the PLTW participants. Besides the quantitative data that was collected, there were several similarities in the ways that the students went about solving the problem.

Of the six PLTW students who were given this ill-defined problem, there was distinctive common pattern when comparing the two female participant results, see Figure 1.1 & 1.2 and Table 4 & 5, participants #2 & #5 were females. Although the research design did not call for comparison of participants' design thinking by gender, the frequency of the cognitive processes of the female students were similar, whereas those of the male students varied. Although these results are interesting, the researchers acknowledge that a greater sample size would be necessary to generalize the finding.

Table 3. Halfin Code (1973)

AN	Analyzing
CO	Computing
DE	Designing
DF	Defining Problems
ID	Interpreting Data
MA	Managing
MO	Modeling
PR	Predicting Results
QH	Questioning / hypothesis

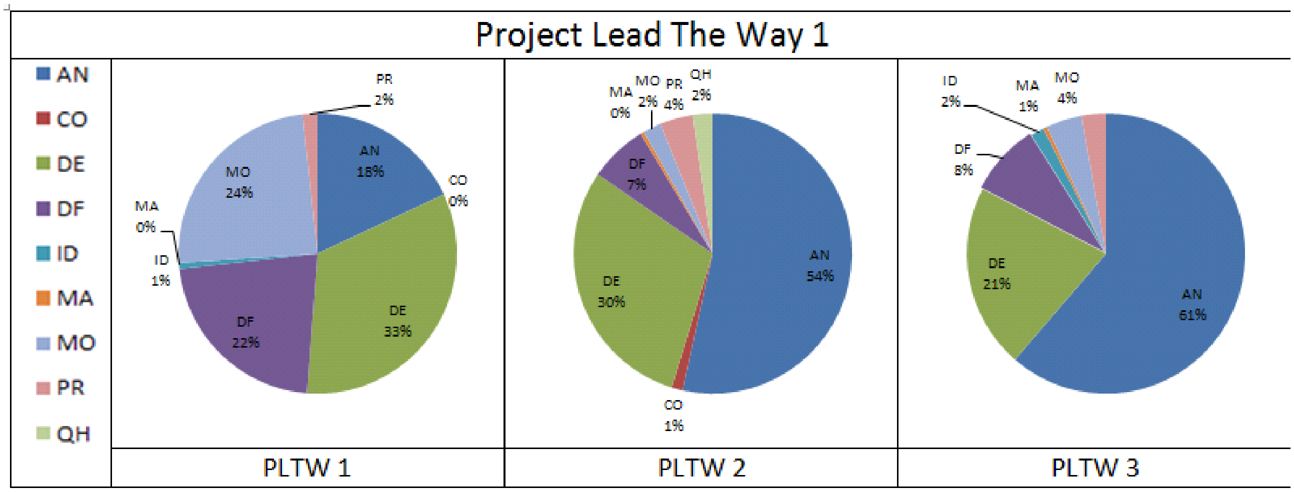

Fig. 1.1: Project Lead Way Participating School #1 Time Breakdown

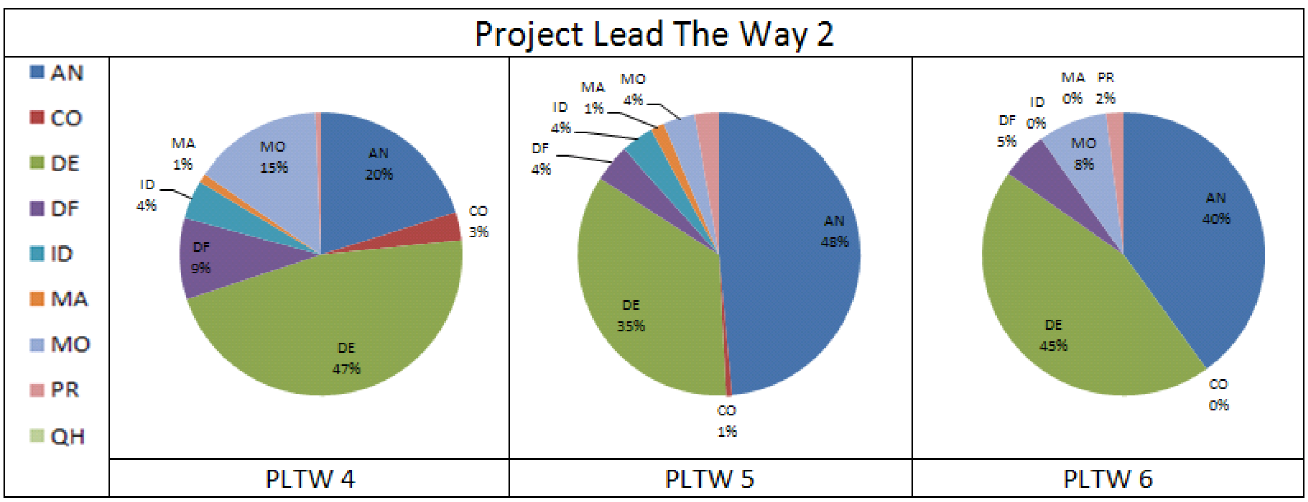

Fig. 1.2: Project Lead Way Participating School #2 Time Breakdown

EPICS High Transfer Problem Results

With the exception of EPICS High participant #3, all other EPICS High students spent 1/3 or more of their time designing solutions with a high of 46 % time on (DE) Designing for EPICS participant # 6 to a low of 20% EPICS participant #3. On average, each EPICS High participant used seven of the nine Halfin coded cognitive strategies. In general the EPICS High students not only employed multiple cognitive strategies but also spent an ample percentage of time employing a variety of strategies. EPICS #1 and EPICS # 6 are the two female participants. See figures 1.3 & 1.4 and Tables 6 & 7.

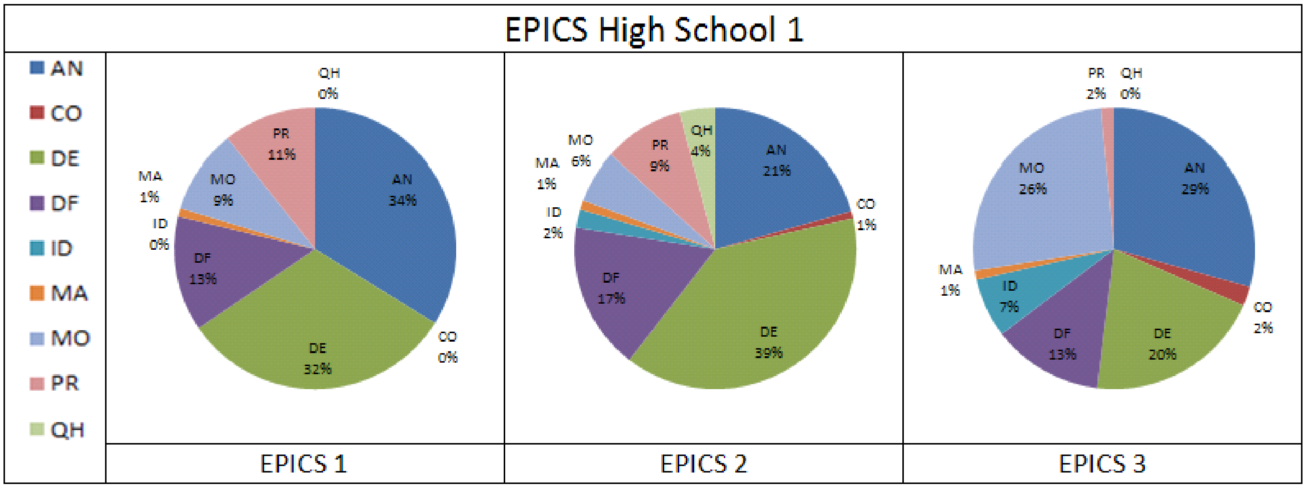

Fig. 1.3: EPICS High Participating School #1 Time Breakdown

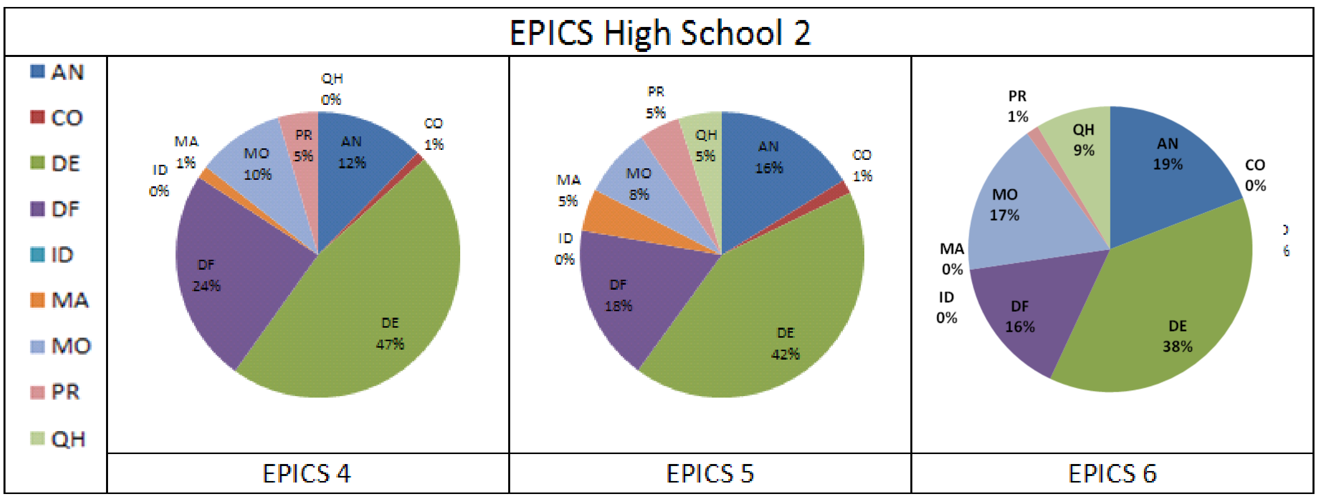

Fig. 1.4: EPICS High Participating School #2 Time Breakdown

PLTW results compared with EPICS High results

The results of the EPICS High transfer problem observational protocol sessions reveal that in general the EPIC High students used a greater variety of cognitive capabilities when designing a solution to the transfer problem compared with PLTW transfer problem results. Clearly, DE (Designing) and AN (Analysis) were the most often employed cognitive strategies for both groups, EPICS High participants employed a variety of other cognitive strategies for an ample amount of time, possibly indicating that the EPICS High students employed a more well-rounded approach to design by employing multiple cognitive strategies. Both groups, with the exception of one participant in each program (PLTW #3 and EPICS #3), employed 1/3 or more of their time on the transfer problem in DE (Designing). This is a promising result because it indicates that the students were able to move successfully from the problem space to the solution space. However, 4 out of the 6 PLTW participants spent 40% or more of their time on (AN) Analyzing. One EPICS High student spent 34% of time on (AN) Analyzing, all other EPICS High participants dedicated less than 30% of their time using Analyzing as a cognitive strategy. It is important to note that the (AN) Analysis Halfin code was recorded by the researchers when participants were observed breaking down the problem and identifying constraints and criteria. (AN) Analysis and (DF) Defining Problems are cognitive strategies that represent the problem space of design thinking. Lawson (1979), identified problem solving strategies as either ‘problem focused’ or ‘solution focused’, and claimed the ‘solution focused’ strategies were more representative of a design-based problem solving strategy.

Only PLTW participants #2 and #3 appeared to be stuck in the problem space, a common pattern for novice designers that limits their ability to generate solutions (Cross & Dorst, 1999; Dorst & Cross, 2001). The PLTW participants that placed emphasis on (AN) Analysis may have been performing this way because the PLTW students have had experience in identifying constraints and criteria in their PLTW course work and classroom activities. For example, the PLTW *Principles of Engineering* marble sorter activity (see description above in classroom observation section of the findings) requires the student teams to troubleshoot problems that occur in their design solutions by identifying the constraints and criteria that are limiting the success of the device. The results of this study indicate that these PLTW students may be transferring their knowledge and experience from the *Principles of Engineering* class to the transfer problem sessions. Although these results appear to identify a program-based impact on students’ ability to transfer their learning to an open-ended transfer problem, too much emphasis on (AN) Analysis can limit students’ abilities to move from problem space into solution space (Cross & Dorst, 1999; Dorst & Cross, 2001).

Limited Mathematical Thinking

Both EPICS High and PLTW students participating in the transfer problem observational protocol sessions had limited employment of (CO) Computing. The Halfin code computing is defined as “The process of selecting and applying mathematical symbols, operations, and processes to describe, estimate, calculate, quantity, relate, and/or evaluate in the real or abstract numerical sense” (Appendix B.) . The researchers did not expect that participants were going to be generating multiple mathematical models to develop solutions to this transfer problem in a 15 to 30 minute test session; however, the transfer problem was created purposely with numbers embedded within the problem to see if students would attempt to quantify, estimate, calculate, or describe design solutions using the numerical information provided within the open-ended problem. None of the six participants spent more than 3% of their design thinking time using the (CO) Computing strategy. PLTW #4 spent the greatest amount of time computing, dedicating 3% of time on this strategy, five other participants (PLTW #1, 3,6 and EPICS #1, 6) never employed computing once during the testing session. This finding reaffirms results in similar studies; for example, Kelley (2008) found that often the participants with the least amount of math instruction employed the most mathematical thinking. PLTW # 4 had only two math courses (Geometry and AP Algebra) but applied the most mathematical thinking, 3% of the time. In contrast, PLTW 5, PLTW 6, EPICS 4, EPIC 5, and EPIC 6, each of whom had five or more math courses, actually employed (CO) Computing for 1% or less of the time. In fact, PLTW 6 had taken six math courses and EPICS 6 had taken five courses, yet neither employed any mathematical thinking during the protocol session. Some leaders in engineering design based instruction at the secondary education level suggest that mathematical modeling and mathematical analysis are key missing pieces in the technological design process (Hailey, et al., 2005; Wicklein, 2006). Although all student participants had taken advanced coursework in mathematics ranging from Algebra 1 through AP Calculus, the participants’ utilization of mathematical strategies was minimal. This finding could cast doubt on the effectiveness of PLTW and EPICS High as effective strategies for improving the applicability of mathematics in engineering design activities.

Design Example Fixation

On the problem statement handout, there was a photo of a school under construction and its surrounding areas; see appendix B. The photo was used to provide a general context to the problem statement. All of the participants referenced the photo at some time in the testing session. Even though the photo was never referenced in the problem statement, all participants devoted attention to an analysis of the photo. Each participant at some point in the testing session used the photo like a template for the location of their playground. This discovery was unexpected; however, Smith, Ward, and Schumacher (1993) reported that providing a designer, whether novice and expert, with a design sample can cause the designer to become fixated on that design example. Such a design sample both limits and influences the designer. Kelley (2008) also found that participants in a similar protocol study were often fixated on the picture that was included in problem statement. Some participants in that study even asked questions about the picture and carefully studied URL citation for the graphic image.

In this study, students were potentially limited in their creative thinking by the context of the photo of a school under construction. This can be an extremely important finding for K-12 engineering educators because it illustrates the potential negative impact of providing an existing design example to students before they generate their own design ideas. There is some concern about the possibility that students may believe that solutions to assigned problems are contained within the student handout.

General Observations across all groups (inter-curricula):

Classroom Layout-The two Project Lead The Way classrooms were arranged differently than a traditional technology education classroom that contains workbenches, industrial machinery, and hand tool cabinets; the PLTW classroom resembled a science lab. The classrooms had only "clean-work" equipment i.e. plotter, 3-D printer, scanners, computers. Although both schools had traditional unit shop facilities within the schools, these facilities were not used for the PLTW classes we observed. EPICS High classes had similar layouts. EPICS High school #1 used a chemistry classroom for the EPICS High course and EPICS High school #2 used a PLTW classroom that was similar to the description of the PLTW classrooms above.

Culture Shift- The general observations of the researchers identified a shift in classroom culture from traditional technology education courses. The researchers not only found the classroom layout and general characteristics of PLTW and EPICS High students to be different from traditional technology education settings but also noted differences in student learning activities and in attitudes toward class activities. The students appear to take more pride in "minds-on" approaches to solving problems and in some cases displayed a lack of interest in hands-on work. This type of thinking could stem from having much of their activities based upon computer work and programming computer controlled machines, especially in the PLTW courses.

Table 4. Project Lead The Way School #1 Transfer Problem Results

	PLTW #1		PLTW #2		PLTW #3		PLTW School 1 Mean Scores	
Halfin Code	Freq.	Time	Freq.	Time	Freq.	Time	Freq.	Time
AN	10	01:38.4	13	05:48.5	11	07:40.3	11.3	05:02.4
CO	0	00:00.0	1	00:08.4	0	00:00.0	0.3	00:02.8
DE	8	03:00.7	8	03:14.2	8	02:39.7	8.0	02:58.2
DF	6	02:00.0	1	00:44.1	1	01:02.8	2.7	01:15.6
ID	1	00:03.8	0	00:00.0	2	00:11.6	1.0	00:05.1
MA	0	00:00.0	1	00:02.8	2	00:03.4	1.0	00:02.1
MO	8	02:12.4	1	00:13.6	1	00:31.1	3.3	00:59.0
PR	2	00:09.5	3	00:25.1	4	00:21.4	3.0	00:18.7
QH	0	00:00.0	2	00:15.0	1	00:01.5	1.0	00:05.5

Table 5. Project Lead The Way School #2 Transfer Problem Results

	PLTW #4		PLTW #5		PLTW #6		PLTW School 2 Mean Scores	
Halfin Code	Freq.	Time	Freq.	Time	Freq.	Time	Freq.	Time
AN	15	02:56.2	34	11:17.1	11	04:19.3	20.0	06:10.9
CO	3	00:27.9	2	00:09.6	0	00:00.0	1.7	00:12.5
DE	17	06:47.2	32	08:06.5	21	09:07.5	23.3	08:00.4
DF	2	01:21.1	3	00:59.2	2	00:58.6	2.3	01:06.3
ID	5	00:38.6	8	00:51.8	0	00:00.0	4.3	00:30.1
MA	2	00:09.0	3	00:21.8	1	00:12.7	2.0	00:14.5
MO	8	02:08.7	6	00:50.6	14	02:00.3	9.3	01:39.9
PR	2	00:05.6	8	00:38.9	1	00:03.9	3.7	00:16.1
QH	0	00:00.0	0	00:00.0	2	00:32.6	0.7	00:10.9

Table 6. EPICS High School #1 Transfer Problem Results

	EPICS #1		EPICS #2		EPICS #3		EPICS School 1 Mean Scores	
Halfin Code	Freq.	Time	Freq.	Time	Freq.	Time	Freq.	Time
AN	4	02:36.4	9	01:52.1	14	04:08.8	9.0	02:52.4
CO	0	00:00.0	1	00:04.5	1	00:18.9	0.7	00:07.8
DE	5	02:26.6	14	03:31.8	14	02:53.0	11.0	02:57.1
DF	1	01:01.2	4	01:39.1	7	01:48.5	4.0	01:29.6
ID	0	00:00.0	2	00:11.4	6	00:57.9	2.7	00:23.1
MA	1	00:04.5	2	00:05.9	1	00:08.9	1.3	00:06.4
MO	3	00:44.4	3	00:32.8	12	03:40.0	6.0	01:39.1
PR	0	00:00.0	4	00:49.9	1	00:12.7	1.7	00:20.9
QH	4	00:49.4	1	00:22.3	0	00:00.0	1.7	00:23.9

Table 7. EPICS High School #2 Transfer Problem Results

	EPICS #4		EPICS #5		EPICS #6		EPICS School 2 Mean Scores	
Halfin Code	Freq.	Time	Freq.	Time	Freq.	Time	Freq.	Time
AN	6	00:40.9	5	00:45.4	5	01:21.6	5.3	00:56.0
CO	1	00:03.5	1	00:04.4	0	00:00.0	0.7	00:02.6
DE	10	02:34.4	7	01:57.8	8	02:40.8	8.3	02:24.3
DF	3	01:20.3	1	00:49.4	2	01:07.1	2.0	01:05.6
ID	0	00:00.0	0	00.00.0	0	00:00.0	0.0	00:00.0
MA	1	00:04.7	1	00:13.3	0	00:00.0	0.7	00:06.0
MO	4	00:32.8	3	00:27.0	6	01:13.7	2.7	00:44.5
PR	3	00:15.1	3	00:13.0	4	00:06.0	3.3	00:11.4
QH	0	00:00.0	2	00:13.8	1	00:36.4	1.0	00:16.7

Inter-rater Reliability Results

Two researchers were used to code the transfer problem observational protocol sessions. The two researchers were trained by the PI of this study how to interpret the Halfin code and how to record the codes using the OPTEMP software. The researchers practiced coding protocol sessions using sample videotape sessions are a part of their data analysis training. Both research assistants were present for all transfer problem sessions and each researcher coded independently using the OPTEM software. Pearson correlation coefficients were calculated to determine how reliable the observational results were for the two independent raters. The Pearson correlation coefficient is identified as a correlation coefficient which applies to interval and ratio level data. The Pearson R was calculated between the two raters for each transfer problem to determine how consistently the raters identified, timed, and reported student's employment of the individual cognitive strategies. A Pearson R of 0 indicates no correlation, a Pearson R of -1 indicates a perfect inverse relationship, and a Pearson R of 1 indicates a perfect positive correlation. The researchers hoped for correlation close to 1, indicating that both raters agree and affirming the reliability of the results. The lowest Pearson correlations were .76 and .75 for PLTW #1 and PLTW #2, the first two transfer problem sessions that were coded by the research assistants. It is logical that the researchers were refining their coding abilities during these first two sessions. Subsequent correlations were .93 or higher, indicating a strong correlation and reliable coding of the transfer problem sessions. See Table 8.

Table 8. Inter-rater Reliability- Pearson R results

PLTW participants	Pearson R	EPICS High Participants	Pearson R
PLTW #1	0.76	EPICS High #1	0.98
PLTW #2	0.75	EPICS High#2	0.99
PLTW #3	0.92	EPICS High #3	0.99
PLTW #4	0.93	EPICS High #4	0.94
PLTW#5	0.99	EPICS High #5	0.94
PLTW#6	0.93	EPICS High #6	0.95

Conclusions / Implications

The researchers acknowledge that classroom observations were limited to approximately 60 students observed in PLTW and EPICS High classes and a sample of 12 participants for the observational protocol, therefore, the results of the study are not generalizable to secondary engineering design programs. The results of this study indicate that students from both engineering design programs successfully develop problem solving abilities to move from problem space to solution space as they worked through an open-ended ill-defined problem. Furthermore, classroom observation revealed that student design teams had healthy design discussions and worked cooperatively to solve technical problems.

However, students were limited in their ability to use mathematical thinking as a design tool to help create design solutions. Although most of the students had advanced math classes; over

50% had 3 or more classes and four participants had five math classes each, students spend 3% or less time using mathematics in their design thinking. This finding confirms prior findings in similar research. Kelley (2008), in a study of two approaches to design instruction that also used a protocol session with a transfer problem, found that mathematical thinking was a limited cognitive strategy employed by the protocol session participants. Moreover, Kelley and Wicklein in a national descriptive study of engineering design curriculum content found a low emphasis on mathematics and engineering sciences in current technology education courses (2009a). Technology education teachers also place a low emphasis on mathematics in student project assessment; the individual item *using mathematics to optimize and predict design results* yielded the lowest percentage of assessment time (Kelley & Wicklein, 2009b). It appears that technology education teachers are not placing great emphasis on using mathematical models to predict design results. Technology education teachers appear to recognize this limitation and have identified it as a challenge. Kelley and Wicklein (in press) in the national status study of technology education regarding engineering design also found technology education teachers identified: *integrating the appropriate levels of mathematics and science into instructional content* as a major challenge in implementing engineering design. More effort is needed to identify appropriate mathematical models and science inquiry examples that teachers can integrate into engineering design activities. EPICS High teacher #2 provided some insight on why students' had limited use of mathematics in the transfer problem in response the question, "Do you believe that your students will employ mathematical thinking (when appropriate) as they work to solve the transfer problem?"

> Yes, I have given similar design problems that required students to use math to solve the problem. However, if students can see that they don't need the math to begin designing then I think they won't use math….if they can find a way to solve the problem without math…they will."

These research findings should be considered by educators and curriculum developers of pre-engineering or secondary engineering design curriculum, of which many also promote these programs as ideal platforms for STEM education. These findings indicate that currently the transfer of STEM learning through the engineering design process on ill-defined problem solving is limited. Engineering design curriculum developers must be more purposeful in creating learning experiences that embed mathematical problems and science inquiry activities into the engineering design process. More efforts need to take place to locate appropriate ill-defined problems that can be explored through the engineering design process that will authentically engage students in the *analysis* and *optimization* stages of the engineering design process. Furthermore, greater efforts must take place across the nation to provide professional development opportunities to assist math, science, and technology education teachers to locate appropriate levels of STEM subjects for delivery in pre-engineering or secondary engineering design curriculum.

Future Studies

This study has provided insight into approaches to teaching engineering design content at the secondary level. Additional research could strengthen the understanding of student learning when engineering design challenges are introduced into secondary classrooms. Consequently, these recommendations for further studies seem appropriate:

(a). Larger observational protocol studies - While insights have been obtained from this study extending prior work (Kelley, 2008), the sample size of 12 is still quite small. There is a need for

observational protocol studies of larger samples of students who are engaged in engineering design activities that incorporate authentic levels of math and science inquiry.
(b) Studies of expert designers - Engineering education can learn from observational protocol studies of expert engineers and expert designers as they working through design problems. For example, observational studies of expert designers can provide insight into typical percentages of time devoted to the respective cognitive capabilities in the engineering design process.
(c) Revisit Halfin's study – A contemporary replication building upon the work of Halfin (1973), who conducted a Delphi study involving ten expert technical problem solvers, and upon the more recent work of Hill (1997) and of Wicklein and Rojewski (1999). Expert technical problem solvers today are expected to employ the engineering design process and to meet the challenges and constraints imposed by the integrated global setting (Friedman, 2005; Pink, 2005).

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Appendix A. Test Session Instructions

Project Title: Cognitive Processes of High School Students Solving Ill-defined Technical Problems

This project has been created to learn about how high school students solve ill-defined technical problems.

This is to inform you about what to expect as you work with me on this research project today.

- I will ask you to fill out a simple survey about the type of classes you have taken in high school.
- I will observe you as you work to solve an ill-defined technical problem.
- I will videotape you as you work through the ill-defined problem. The purpose of the videotape is to provide a backup record of the test session and only will be used to verify the coding process. No one other than a fellow researcher and I will view the videotape of your problem solving session and the tape will be erased when I complete my research.
- I will also be taking notes and using a computer program while you are working to solve the ill-defined technical problem. The computer is used to record your thoughts and processes by using a special coding process that I enter using the keyboard.
- Your participation in this project will not affect your grades in school. I will not use your name on any papers that I write about this project.
- If you want to stop participating in this project, you are free to do so at any time. You can also choose not to answer any question.
- Don't worry about getting the right answer; as with most design challenges there is more than one right way to approach a problem and develop a solution.
- If you have any questions about this testing session or process, feel free to ask me. If you have questions as you work through the problem, feel free to express them; however, I may not be able to answer. I am looking for your thoughts to this problem.
- I will encourage you to keep talking through your thought process as you work on the ill-defined problem.
- You can take a break at any time if you need one. Just let me know if you need a break and we can pause the camera and computer program.
- I encourage you to NOT talk with other classmates about this session until tomorrow.

If you have any other questions at this time feel free to ask. Thank you for taking the time to help me on this research project.

Sincerely

Dr. Todd Kelley

Appendix B. Transfer Problem

Problem

A new K-5 elementary school has been constructed in the local area and new playground still needs to be designed. You obtained the following specifications:

The school is expected to have around 500 students. The area of the playground has not been determined and space is limited. Safety of both students and school properties needs to be considered. For example, if students are playing softball too close to a building, they would risk breaking windows. At minimum, one entire grade will use the playground space at once. The playground needs to be attractive and fun for all students.

Your Task

Describe how you would design the playground for the school in the problem statement. Please describe all assumptions, information you need to obtain, and justification of use of space as you “think aloud” your strategies for developing the solution.

Appendix C. Merriam's Observational Element Guidelines

Merriam (2001) suggests six elements to consider when making observations. The following elements will be used as a guide when making classroom observations for this research and have been modified to address specific issues in this construct.

1. *Physical setting*: What is the technology classroom like? How is it decorated and arranged? Where is the classroom location in the school building? What objects and artifacts are in the classroom? What other resources such as computers, equipment, etc are present?
2. *The participants*: Who is in the classroom? Who are the students who are taking the engineering design course? What are the commonalities of these individuals? What are the differences of these individuals? What demographic is underrepresented? Who may be overrepresented?
3. *Activities and interactions*: What types of activities are taking place in the classroom? How do participants interact with the activity and with each other? What are the objectives for the class? How are these objectives achieved? How are these objectives achieved? (Note: some of these questions may be revealed through curriculum documents).
4. *Conversations*: What is the content of the conversations in this classroom? Who is speaking? Who is silent? What is being said nonverbally? Direct quotes from the class will be used when possible.
5. *Subtle factors:* Informal or unplanned events. Nonverbal communication. Dress and physical appearance of participants. What events do not occur that should occur?

Appendix D. The Cognitive Processes identified by Halfin's 1973 Dissertation Study

The Original Cognitive Processes identified by Halfin's 1973 Study of High-level Designers		
Proposed mental methods		**Definition**
Analyzing	AN	The process of identifying, isolating, taking apart, breaking down, or performing similar actions for the purpose of setting forth or clarifying the basic components of a phenomenon, problem, opportunity, object, system, or point of view.
Communicating	CM	The process of conveying information (or ideas) from one source (sender) to another (receiver) through a media using various modes. (The modes may be oral, written, picture, symbols, or any combination of these.)
Computing	CO	The process of selecting and applying mathematical symbols, operations, and processes to describe, estimate, calculate, quantity, relate, and/or evaluate in the real or abstract numerical sense.
Creating	CR	The process of combining the basic components or ideas of phenomena, objects, events, systems, or points of view in a unique manner which will better satisfy a need, either for the individual or for the outside world.
Defining problem(s)	DF	The process of stating or defining a problem which will enhance investigation leading to an optimal solution. It is transforming one state of affairs to another desired state.
Designing	DE	The process of conceiving, creating inventing, contriving, sketching, or planning by which some practical ends may be effected, or proposing a goal to meet the societal needs, desires, problems, or opportunities to do things better. Design is a cyclic or iterative process of continuous refinement or improvement.

Experimenting	EX	The process of determining the effects of something previously untried in order to test the validity of an hypothesis, to demonstrate a known (or unknown) truth or to try out various factors relating to a particular phenomenon problem, opportunity element, object, event, system, or point of view.
Interpreting data	ID	The process of clarifying, evaluating, explaining, and translating to provide (or communicate) the meaning of particular data.
Managing	MA	The process of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system.
Measuring	ME	The process of describing characteristics (by the use of numbers) of a phenomenon problem, opportunity, element, object, event, system, or point of view in terms which are transferable. Measurements are made by direct or indirect means, are on relative or absolute scales, and are continuous or discontinuous.
Modeling	MO	The process of producing or reducing an act, or condition to a generalized construct which may be presented graphically in the form of a sketch, diagram, or equation; presented physically in the form of a scale model or prototype; or described in the form of a written generalization.
Models/prototypes	MP	The process of forming, making, building, fabricating, creating, or combining parts to produce a scale model or prototype.
Observing	OB	The process of interacting with the environment through one or more of the senses (seeing, hearing, touching, smelling, tasting). The senses are utilized to determine the characteristics of a phenomenon, problem, opportunity, element, object, event, system, or point of view. The observer's experiences, values, and associations may influence the results.

Predicting	PR	The process of prophesying or foretelling something in advance, anticipating the future on the basis of special knowledge.
Questions/hypotheses	QH	Questioning is the process of asking, interrogating, challenging, or seeking answers related to a phenomenon, problem, opportunity element, object, event, system, or point of view.
Testing	TE	The process of determining the workability of a model, component, system, product, or point of view in a real or simulated environment to obtain information for clarifying or modifying design specifications.
Visualizing	VI	The process of perceiving a phenomenon, problem, opportunity, element, object, event, or system in the form of a mental image based on the experience of the perceiver. It includes an exercise of all the senses in establishing a valid mental analogy for the phenomena involved in a problem or opportunity.

Appendix E. Research Poster

Appendix F. Teacher Follow-up Questions

Good Morning,

I have completed the final report for the PLTW/ EPICS High study and would like to share the results with you, but before I do I have a few follow-up questions that I believe would only take about five minutes to complete. Feel free to answer them within this e-mail.

How do you think your students did on the transfer problem? The results revealed that there were two general patterns of design thinking, students in general were either *Problem Focused* or *Solution Focused*. *Problem Focused* is when students focus a majority of their time defining the problem and identifying constraints and criteria. *Solution Focused* is when students focus on brainstorming ideas and sketching. Based upon the assumption that all of your students performed similarly:

1. Do you think that your students who participated in the transfer problem were Problem Focused or Solution Focused?

2. Based upon your response to question #1, do you believe that students solved the transfer problem in a similar way to which they might solve a problem in your class/curriculum?

3. Do you believe that in general, students use the design process as a universal problem solving process?

4. Do you believe that your students will employ mathematical thinking (when appropriate) as they work to solve the transfer problem?

5. Do you believe, based upon your students experiences in your class (PLTW or EPICS) that the students are prepared to engage in solving open-ended problems using STEM (Science, Technology, Engineering, Mathematics) thinking?

Appendix G. Teacher Follow-up Responses.

PLTW # 1 Teacher Follow-up Response.

1. Do you think that your students who participated in the transfer problem were Problem Focused or Solution Focused?

I think that my students were solution focused. They generally tried to create a solution, then go back to see if it fits within the constraints.

2. Based upon your response to question #1, do you believe that students might solve the transfer problem in a similar way to which they might solve a problem in your class/curriculum?

Yes, I believe that the students would approach problems in my classroom the same way they approached the transfer problem. Their approach to a problem, in my observation, tends to be habitual, and tied into their personality as much as anything.

3. Do you believe that in general, students use the design process as a universal problem solving process?

I do not believe that students generally approach problem solving using the problem solving process taught in PLTW. Some students formulate solutions and use guess and check to see if they fit the constraints. Some start with a concept of a solution, and fill in details that make it fit the constraints. They are prone; in particular, to immediately start judging solutions during the brainstorming phase.

4. Do you believe that your students will employ mathematical thinking (when appropriate) as they work to solve the transfer problem?

Again, I believe this varies with each student. I think this may dependent on learning style. Students who are visual learners may try focusing more on prototyping and sketching to figure solutions. Students who are more abstract in their thinking may use a more mathematical approach

5. Do you believe, based upon your students experiences in your class (PLTW or EPICS) that the students are prepared to engage in solving open-ended problems using STEM (Science, Technology, Engineering, Mathematics) thinking?

Of the students in my PLTW class, I believe most of them are prepared to approach open-ended problems in the STEM arena. My experience with PLTW is that students get out of it what they put into it. Students who do not put forth much effort in the class will probably not be as prepared to engage in these problems as students who were more attentive and conscientious throughout the course.

PLTW #2 Teacher Response:

1. Do you think that your students who participated in the transfer problem were Problem Focused or Solution Focused?

I would assume that my students were solution focused. It seems that with a lot of the PLTW projects more emphasis is put on the final product or solution to the problem. Many of my students rush to sketch ideas out on paper to solve the problem.

2. Based upon your response to question #1, do you believe that students might solve the transfer problem in a similar way to which they might solve a problem in your class/curriculum? **Yes, as I stated in my previous answer about the PLTW curriculum seems to put more emphasis on the final product and not on the problem.**

3. Do you believe that in general, students use the design process as a universal problem solving process?
No, I believe most students use the scientific process to solving problems. Both processes have similar steps within each of them to help solve the problems.

4. Do you believe that your students will employ mathematical thinking (when appropriate) as they work to solve the transfer problem?
Yes, my students were taught at a young age and continue to learn that they need to follow a series of steps to solve math problems. By learning to solve problems this way, it probably carries over to solving the transfer problem as well.

5. Do you believe, based upon your students experiences in your class (PLTW or EPICS) that the students are prepared to engage in solving open-ended problems using STEM (Science, Technology, Engineering, Mathematics) thinking?
I would say yes, that most of my students are prepared to engage in solving open-ended problems using STEM, but in reality I know some of my students would still need extra help (ex. many questions to ask for clarification about the problem) in solving the problem.

EPICS #1 Teacher Response:

1. Do you think that your students who participated in the transfer problem were Problem Focused or Solution Focused?
I would assume that the students were more problem focused
2. Based upon your response to question #1, do you believe that students might solve the transfer problem in a similar way to which they might solve a problem in your class/curriculum?
Yes, the students in class are often caught up in the problem and struggle to see solutions.

3. Do you believe that in general, students use the design process as a universal problem solving process?
No, most students in my class just try and try again, without focusing on a solution.

4. Do you believe that your students will employ mathematical thinking (when appropriate) as they work to solve the transfer problem?
No, the students are too methodical in how they approach problem solving.

5. Do you believe, based upon your students experiences in your class (PLTW or EPICS) that the students are prepared to engage in solving open-ended problems using STEM (Science, Technology, Engineering, Mathematics) thinking?
Yes, many can use these skills effectively if they take the time to evaluate.

EPICS #2 Teacher Response:

1. Do you think that your students who participated in the transfer problem were Problem Focused or Solution Focused? **The students would be solution focused I think.**

2. Based upon your response to question #1, do you believe that students might solve the transfer problem in a similar way to which they might solve a problem in your class/curriculum?
Yes, I would hope that the students would transfer their learning from my class.

3. Do you believe that in general, students use the design process as a universal problem solving process? **Yes, in our area (technology education) but school wide no.**

4. Do you believe that your students will employ mathematical thinking (when appropriate) as they work to solve the transfer problem?

> **Yes, I have given similar design problems that required students to use math to solve the problem. However, if students can see that they don't need the math to begin designing then I think they won't use math….if they can find a way to solve the problem without math…they will**.

5. Do you believe, based upon your students experiences in your class (PLTW or EPICS) that the students are prepared to engage in solving open-ended problems using STEM (Science, Technology, Engineering, Mathematics) thinking?

Yes, I believe that they have the ability to use STEM thinking.