

AC 2009-1678: HIGH SCHOOL TEACHERS ENGINEERING DESIGN LESSON PLANNING THROUGH PROFESSIONAL DEVELOPMENT

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“The vast majority of Americans will never become engineers, but all Americans - young and old - can benefit by having a better understanding of the role engineers play in the creation of technologies”¹. The relationship between understanding engineering and technological literacy is of special urgency during the high school years, since “technologically literate people should also know something about the engineering design process”². Developing students’ understanding of engineering design is aligned with the Standards for Technological Literacy Standard 9³. The focus of this study is on development of teachers’ understanding of engineering design in preparation for infusing engineering design into their high school classrooms, as evidenced by their lesson plans.

The National Center for Engineering and Technology Education (NCETE) provided professional development with the following goals: a) increase teachers’ subject matter knowledge in engineering design and strengthen their mastery of pedagogical content knowledge related to the infusion of design experiences into their courses; b) apply principles and practices of engineering design as teachers work individually and in small groups to develop solutions to technical problems; and c) identify and select design challenges and instructional materials that will motivate and enable teachers’ students to move efficiently through learning progressions in engineering design⁴.

NCETE Teacher Professional Development

Positioning of the teacher as developer of lessons facilitates coherence with other learning activities occurring in each teacher's classroom. Specifically, teachers can situate the engineering design concepts into their curriculum by crafting a lesson rather than attempting to fit a pre-packaged generic lesson into an existing and, perhaps, rigidly structured curriculum. The lesson development opportunities provide teachers with an active learning experience, wherein they first experience exemplary engineering design challenges as participants and then create design challenges. Formative feedback was provided by peer teachers and professional developers as the teachers developed the lessons. To facilitate the integration of engineering into the classroom through lesson planning, the professional development team was comprised of technology education teacher faculty and engineering faculty. While teachers were engaged in lesson development, additional subject matter experts were invited to participate representing various engineering disciplines, mathematics, and physical sciences, as well as instructional technology specialists. This broad team of professionals provided support and guidance in the lesson development process.

Engineering Design Defined

Engineering design has been defined by the Accreditation Board for Engineering and Technology ⁵:

Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.

Sheppard, Macatangay, Colby, and Sullivan state that “engineering design involves a way of thinking that is increasingly referred to as design thinking: a high level of creativity and mental discipline as the engineer tries to discover the heart of the problem and explore beyond the solutions at easy reach”⁶. The NCETE professional development approach emphasizes eight essential elements of the engineering design process appropriate for high school learners⁷: a) identification of a need, b) definition of the problem/specifications, c) search, d) develop designs, e) analysis, f) decision, g) test prototype and verify the solution and, h) communication .

These eight steps are generally congruent with introductory college level texts describing the engineering design process for engineering students⁸⁻¹¹. Design is recognized as the critical element of engineering thinking which differentiates engineering from other problem solving approaches¹². The engineering design process, as noted by Sheppard et al. , “is not linear: at any phase of the process, the engineer may need to identify and define subproblems, then generate and evaluate solutions to the subproblems to integrate back into the overall process”⁶. Sheppard et al. summarized the design process to include three broad areas of focus: defining the problem, generating candidate solutions, and evaluating and implementing candidate solutions, and added that communication, teamwork, time management, and project management were essential broader professional skills requisite to success⁶.

In distinguishing the engineering design process from other problem solving models, the role of analysis cannot be overstated. Analysis provides insights to the decision making process through application of mathematics and science. “The engineering sciences have their roots in mathematics and basic sciences but carry knowledge further toward creative application. These studies provide a bridge between mathematics and basic sciences on the one hand and engineering practice on the other”⁵. As posited by Hailey, Erikson, Becker, and Thomas¹³, in

engineering, analysis is presented as a decision-making tool for evaluating alternative designs. For NCETE, one critical goal is to introduce high school students to the vital role of analysis in the engineering design process. This would presumably allow technology education to serve as an integrator of mathematics and science for a diverse array of learners¹³. As a result of the Center's emphasis on teaching the role of analysis in problem solving, professional development efforts centered deliberately on the introduction of analysis.

Purpose of the Study

The purpose of this qualitative case study was to describe the engineering design process lesson planning that teachers generated during professional development. This study is guided by the following research question: How do high school STEM teachers plan to implement engineering design in their classrooms? Researcher understanding of teachers' planned implementation emerged through the triangulation of data which included teacher generated lesson plan documents and lesson presentations during the professional development. The sample of 17 teachers participating in this study represent science, mathematics, and technology education teachers who work under the constraints of standard-based curriculums. Data considered in this study were limited to professional development experiences and was not inclusive of observations of teaching behaviors situated in teachers' classrooms.

Methodology

A multisite case study approach formed the methodology for this study, utilizing the coordinated professional development efforts of a historically black university on the east coast and an urban southern California campus. According to Creswell,¹⁴ case studies are a qualitative research approach utilized to explore programs, activities, and more than one individual in depth. Case studies are bound by time and activity, an approach by which the researchers collect

detailed information using a variety of data collection procedures. For this study, five different observers were responsible for collecting data on the professional development and participant teacher presentations. Professional Development was conducted at two universities and served teachers of Science, Technology, Engineering and Mathematics (STEM). Observational data were collected by naturalistic participant observers at each research site. Descriptions written up by the observers were compiled for analysis. Teacher generated lesson plan documents were collected by the observers and archived for analysis. A team of evaluators collected survey data from each participant which was also utilized in this study to provide demographic data on participants.

Participants

Professional development participants were solicited by advertisement and principal recommendation. Teachers involved in the professional development were selected for this study if they regularly attended the sessions, developed a lesson plan to integrate engineering design in the classroom, and presented it to the peer group (which was an expectation of the participants by the professional development team). Data were collected on 17 high school teachers from California, North Carolina, and Virginia. The participants represented a variety of racial and ethnic backgrounds including Caucasian (58.8%), Latino/Latina (14.6%), Asian (11.8%), African American (5.9%), and Native American (5.9%). The majority of participants were male (58.8%).

The majority of teachers indicated majoring in science, math, technology, or education as undergraduates. Nearly 60% of teachers had certification in mathematics education; 12% of teachers were certified in science education; and 47% held certification in technology education. Seventy-six percent of the participants had obtained, or were actively pursuing, a graduate level

education. All of the teachers reported experience in teaching students between tenth and twelfth grade. The average number of years teaching was eleven with a range of one to thirty-two years. Participant teaching assignments for the academic year following the start of the professional development program included math (58.8%), science (11.8%), and technology education (47.1%).

Analysis

Near the conclusion of the professional development, teachers presented their lessons infusing the engineering design process into the classrooms. To develop an understanding of how teachers plan to implement the engineering design process, the collected data were analyzed with a focus on the teachers' plans for how engineering design would be employed in their classrooms. Creswell¹⁵ indicated that "description" is a form of case study analysis that involves the researcher providing a detailed view of aspects regarding the case. The authors of this study employed a "descriptive" case study approach to analyze the qualitative data. This approach involves identifying the setting and/or individuals, followed by analysis of the data for themes¹⁴. This type of data analysis encompasses a detailed description of the case that emerges which is followed by an analysis of generated themes and an interpretation of the case.

For this study, analysis followed an iterative nature of qualitative inquiry, wherein the authors independently reviewed the observational data and identified elements of the engineering design process and emergent themes. In collaboration, the authors discussed emergent themes and the appropriate use of the eight elements of the engineering design process, generated a priori by the leadership of the professional development. With consensus of the coding schema, a graduate student was employed to code lessons created by the teachers. The authors reviewed the graduate student's coding in an effort to develop collaborative consensus on the appropriate

meaning of coded segments of data from lesson plans, observations, and evaluative data. Teacher generated lesson plans (e.g., student handouts/presentation notes and multimedia references), field notes detailing teacher presentation of their lesson plan in front of their peers (and professional development team) for critique which were included in the analyses.

Findings

Careful analysis and discussion by the research team produced evidence supporting the inclusion of eight engineering design elements from the participants' lesson plans, observation notes, and survey data. Typical of the majority of the teacher participants was a hierarchal approach to orchestrating the use of engineering design challenges in the classroom. In this model, teachers would begin the design process and narrow the problem definition and potential solutions prior to engaging their students. The students would employ the design process on a reduced solution set, identifying the most optimal solution using the teacher refined problem definition.

Generally, engineering design challenges developed by the participants were divided into teacher responsibilities and student responsibilities. In providing a more structured problem suitable for novice learners, students were responsible for gathering information and data relevant to the design problem, performing analysis on alternative solutions provided by the teacher, testing and verifying models, and communicating the results of the analysis. Teacher responsibility included identifying the need, defining the problem, developing and deciding on alternative solutions. Several teachers did not produce lesson plans that provided sufficient evidence of an engineering design challenge, and, therefore, these three teachers did not inform model development.

Exemplary Cases

In providing evidence of the participants' progression through the engineering design process, the researchers are including exemplary cases. The described cases of the teachers' lesson plans highlight prominent examples of the engineering design process.

Identification of the Need

According to the engineering design model utilized by the professional development team, the first element is to identify a need. This is usually performed by a client, supervisor, outside customer, or another group with an engineering design firm. The teachers performed the need identification which involved identifying a lack or shortage of something that is essential or highly desirable. A technology education teacher articulated the need for a design in his lesson plan intended for a 10th grade mechanical drafting course:

For decades the Panama Canal set the standards for ship building, but today the world of commercial shipping is building bigger, heavier and faster ships known as “mega ships”.

The Panama Canal Authority is faced with a huge challenge, do they gamble millions [of dollars] to widen the canal or lose revenue.

Observations of this presentation noted that this teacher introduced this need with a multimedia presentation. A video entitled *Extreme Engineering* described the industry's demands for larger ships and the dilemma of longer travel times around Panama versus challenges associated with widening the Canal to handle larger ships.

Definition of the Problem

The next element in the engineering design process, and possibly the most important, is defining the problem. This element includes fully understanding what the client wants and needs. Oftentimes, the need will be guided by the design constraints or specifications which must be followed throughout the engineering design process. In a pre-calculus lesson integrating alternative energy and parabolic solar hot water heating, the problem was defined as follows:

Using the data above for approximate water usage [and wattage estimation table to heat water in one hour], calculate how much water your family uses for their morning/evening showers and how large the surface area of your solar reflector would have to be to heat your household water at least 20 degrees above ambient temperature.

In presentation, she articulated that the students would calculate the water demands, calculate the [parabolic dish] area required, and build a reflector that would meet the hot water needs of a family. An essential element of the student's problem was identified by the lesson plan as creating a scale model and comparing measured values to the calculated values.

Search (Gathering Information)

Next in the engineering design process as cited by the professional development team is the gathering of information. This element involves accumulating knowledge about the identified need by collecting data and other useful information and often leads to additional questions requiring further research. The collected information must then be reviewed and organized. An Algebra Two teacher sought to calculate horizontal distance in a projectile motion problem. In the lesson plan, students were expected to search for information:

Do some research on the physics behind the problem. What type of equation would best model the path of the stuntman? What type of net or inflatable would be best for catching the stuntman?

The lesson also detailed how students would gather information on their teacher provided launcher:

To predict where a projectile will hit the floor when it is shot from a location at some predetermined angle above horizontal, it is necessary to first determine the initial velocity of the object.

The lesson detailed an eight step procedure for the students to follow to measure initial velocity beginning with a horizontal launch relating the initial launcher height and horizontal travel distance to initial velocity.

Developing and Evaluating Alternative Solutions

After gathering the information, the next element in the engineering design process is developing and evaluating alternative solutions. This element involves generating a list of possible solutions for the problem. Usually, it involves little or no scientific analysis.

Brainstorming is frequently employed to develop a list of ideas. Using the information gathered in the design process, one might identify key factors that will govern the design. In a lesson plan targeting two, 45 minute periods, a geometry teacher presented this development of alternative solutions for runaway trucks:

There are three types of truck ramps to consider: arrester beds, gravity escape, and sand pile escape. Arrester beds are ramps adjacent to the road filled with some type of material

that allows the truck to come to a stop with the help of rolling resistance. Common materials include sand and gravel. Gravity escapes on long upgrades parallel to the road. A long length of road is required. The drawback to this model is that the trucks will roll backwards after stopping their forward motion, making it difficult for the driver to maintain control. Sand pile escapes have short lengths and are filled with loose sand. The drawbacks to this option are the fact that the trucks decelerate quickly, which may cause injury to the driver or damage to the truck, and the fact that the sand can become useless and harmful due to the weather.

Based on analysis and optimization, she planned for students to determine the optimal solution, balancing costs, and function. Teacher participants were, generally, responsible for generating alternative solutions and narrowing this list for the students.

Analysis

In this element of the design process, alternative solutions are analyzed using math and engineering principles to determine their performance capability, costs, and efficacy on other pertinent criteria. Calculations are performed and the results checked for reasonableness. An example of analysis was detailed in a technology education teacher's lesson on parachute design in order to determine parachute diameter. In mathematical form, the relevant variables are expressed as:

$$D = \sqrt{(8 m g) / (3.14 \rho C_d v^2)}$$

where

D = the chute diameter in meters (solve for D)

m = the rocket mass in kilograms

g = the acceleration of gravity = 9.81 m/s^2

ρ = the density of air = 1.22 kg/m^3

C_d = the drag coefficient of the chute, 1.5 for a parachute (dome-shaped chute)

v = the speed we want at impact with the ground (3 m/s or less)

The technology education teacher then presented an example using the equations to predict the diameter of a parachute required for a model rocket, finding it to be 17.1 inches in diameter.

The teachers planned to provide analysis methods for the students, but the students will conduct the analysis. In most cases, students were expected to perform analysis on alternative solutions generated by the teacher participants.

Decision

This element of the design process uses data collected in the information gathering and analysis phases to determine the best solution to satisfy the identified need and specific problem. Generally, teachers' lessons stated that a decision would be made, but little evidence was provided detailing how students would choose the optimum solution. A technology education teacher stated in his lesson plan:

Using all of the previous information a decision on the best solution is proposed. The best solution is the one that best satisfies the client's needs. The best solution is not always the cheapest or most elegant but is the one that satisfies your design criteria the best. This often involves tradeoffs or compromise.

Tradeoffs are usually a consideration in the decision making process. The teachers made some initial decisions to limit the solution set, but the students were responsible for considering how each solution met the criteria to optimize their decision making process. Observers noted that a math teacher stated that she planned for students to test four designs of a road bed that would safely stop a runaway truck. Students were to gather data on material costs, volume and length required to calculate the most effective solution.

Testing and Verifying the Solution

Once a decision has been made, the next element of the engineering design process is testing and verifying the solution. This involves verifying that the chosen decision meets the design constraints or specifications. Typically, a physical model or prototype can be constructed and tested to verify its validity. However, in the case of a complex or expensive system, a computer-based model may be tested to verify the solution. All teacher participants involved in the professional development developed models or prototypes that allowed their students to test and verify the selected solutions. In a mathematics teacher's lesson on functions, statistics and trigonometry for juniors and seniors, the following data were required of the students:

Now, test out your function four times, each time with the different independent variables (times) shown below. Record your theoretical values, experimental values, and variances

in the table below. Show your work in finding the theoretical values in the space below the table.

Time	Theoretical height	Experimental height	Variance
15 seconds			
30 seconds			
45 seconds			
60 seconds			

Are your variances small? Are they consistent? If your experimental values are nowhere near the theoretical values, then you may need to go back and look for mistakes, either in your measurements or your computations.

Participant observers documented that teachers were acting as students, making predictions based on rotation and position, using circular motion equations and verifying their measurements in an experimental laboratory setting.

Communication

Once a decision was made and experimentally verified, students were responsible for communicating the results to the teacher. Teacher participants involved in the professional development generally required that their students keep an engineering design notebook detailing their elements within the engineering design process. As an example, a geometry teacher planned to require her students to write to their city's transportation division, communicating findings, decision, and design specification:

Write a letter to *Caltrans* to communicate your findings. Tell them which aggregate you would choose and why. Include in your letter the length the truck bed should be, the maximum weight for trucks to use this road safely, and the expected cost of filling the bed. Include a bar graph for each car representing how far it rolled in each aggregate. Also, create a bar graph comparing the cost of each aggregate when stopping the orange car.

Conclusion

Most teachers (14 of 17) who completed the professional development created lesson plans which involved the engineering design process. Teachers' planned use of the engineering design process in their classrooms provided evidence of their interpretation of engineering design. The engineering design process, as defined by the eight element model promoted by the National Center for Engineering and Technology Education, was evident as a planned collaborative experience between teachers and their students. Teachers planned for a general shift in responsibilities as students progressed through the design process. In the early stages of the design process, teachers had the majority of responsibility for identifying the need and defining the problem. This may be attributed to the difficulty novice learners encountered by attempting to define the problem, which is consistent with the literature, "If the problem is not well defined, considerable effort must be expended at the beginning in studying the problem, eliminating the things that are unimportant, and focusing on the root problem. Effort at this step pays great dividends by eliminating or reducing false trials, thereby, shortening the time taken to complete later steps" ¹⁰. Teachers planned to do most of the research and develop a limited set of designs with which the students might work. Student responsibilities increased as they began with a limited solution set and conducted analysis planned by the teacher. Students made a

decision based on the analysis and tested their predicted results with experiments planned by the teacher. It was solely the students' responsibility to communicate their results, often in a mock presentation, sharing their findings and justifying their decisions with data.

Implications

Professional development by a team of STEM experts can induce a change in teacher pedagogy. Traditional practices of teacher-led instruction will not suffice for teachers seeking to introduce engineering design challenges in their classroom. Teachers planning to implement engineering design in their classrooms are faced with a multitude of obstacles including, but not limited to their inexperience in teaching engineering design elements, their students' math and science aptitude, the challenge of working with novice learners, and constraints of working within a standards-based curriculum. Teachers, adept at instruction, should note the concerns of introducing open-ended and ill-defined problems into their classrooms. To counteract this concern, teachers involved in the NCETE professional development took an approach to engineering design that allowed for collaborative problem solving, wherein the teacher gradually shifted the responsibilities of the engineering design problem to the student as the problem became more defined and structured.

This study has implications for further professional development efforts which seek to develop STEM teachers with the capacity to infuse engineering design into their classrooms. Implications are also evident for teachers seeking to introduce engineering design concepts into their curriculum. In addition to sharing responsibilities with their students, teachers introducing engineering design concepts in their classroom should provide ample feedback and mentoring as students matriculate through an engineering design problem. Future studies should investigate

the cognitive processes of students as they progress from structured problems to ill-defined, open ended problems.

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