High School Students' Application of the Engineering Design Process

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Abstract— This work-in-progress paper examines the engineering design process to emphasize open-ended problem solving that encourages students to design, test, and learn from their trials. This process nurtures students' abilities to create innovative solutions to challenges in any subject. Integration of engineering design into secondary experiences is a supportive context for STEM learning. Such experiences introduce students to the nature of engineering and provide opportunities to experience how engineers respond to emerging challenges. These experiences are important in promoting an understanding of engineering and cultivating interest in the profession. The engineering design process engages students in identifying a problem, developing possible solutions, making a prototype, testing and evaluating, modifying and retesting, and communicating results. The last stage in this process extends the common five stage approach, recognizing the critical nature of scientific communication in sharing results. It is essential for students to become familiar with the process as they develop their design thinking, and model the processes used by engineers. This study explores students' use of the engineering design process by analyzing students' written engineering design reports that were composed and submitted for a STEM competition at the secondary school level. Researchers used the six phases of the design process as a lens to explore students' demonstration of each component. Preliminary results of the thematic analysis show that students identify design challenges to address, usually in the form of "I will engineer a XXX that will address YYY" where the problem and engineering solution are specified. Though students provide critical information on their design steps, steps are often not detailed enough to convey the actual process taken in design and testing. Students engage in a iterative process of testing, addressing issues, retesting, but often do not describe the retesting process or final changes. Data is often summarized in narrative form with limited attempts to incorporate tables, graphs, and illustrations to communicate design features and data from trials. Students summarize their findings but often fail to use language that conveys how the outcomes address the stated problem or challenge. This paper describes salient findings for each of the six engineering design phases.

Keywords—design process, design projects, high school

I. INTRODUCTION

The engineering design process is critical to guide the development of new products. The engineering design process as it we have applied it to scientific disciplines includes six steps [1]: identifying a problem, developing possible solutions, making a prototype, testing and evaluating, modifying and retesting, and communicating results

In addition to the widely recognized first five phases, we emphasize the sixth phase, 'communication,' recognizing the critical role of describing the details of the process to multiple audiences. Communication is intricately linked to evaluating and improving designs [2].

This research focuses on design projects reported upon by high school students in the United States. It is important to understand how students respond to engineering design challenges and how their thinking and implementation of the process is characterized. Berland, Stingut & Ko [3] found that high school students better understand and value qualitative aspects than those that are more quantitative, though integration of mathematics and science into the projects is critical to quality products. Relatedly, Becker & Mentzer [4] studied design challenges from fifty-nine high school students across four states. They concluded that students spend little time gathering information and in the 'problem-scoping' stage. They also found that students do not understand problems from clients' perspectives and spend little time investigating the feasibility of an idea or in evaluating alternatives.

II. APPROACHES TO DESIGN AS OPEN-ENDED PROBLEM SOLVING

Among the first to formally address engineering design as open-ended problem-solving was Herbert Simon. He was trying to understand and describe design. In *The Sciences of the Artificial*, Simon [5] identified design as knowledge in the domain of professions like engineering, management, or medicine. He believed that these professions have as their central concern problem-solving, in the sense of working toward "what ought to be" in contrast with the pure sciences, which are concerned with "what is." He later extended his approach to include ill-defined problem-solving of all kinds [6]. By contrast, in Christopher Alexander's view [7], designers are privileged makers who create specific form through their understanding of materiality. This is the tradition of professional and craft design that creates specific kinds of objects, custom musical instruments, chairs, or clothing designs. Simon, on the other hand, argues that designers' work is abstract and that their role is to create a desired state of affairs, and that this way of thinking about design should be central to all professions. More recently, Kees Dorst and Nigel Cross [8] argue that problems and solutions co-evolve, and as Lucy Kimbell [9] notes, this approach gives designers more explicit agency in problem-solving. This co-evolution model emphasizes transfer of knowledge between problem and solution spaces highlighting the critical nature of both problem understanding and solution generation.

We conceive of engineering design as an open-ended problem-solving process, iterative in nature, that can be characterized by six stages (see Fig. 1):

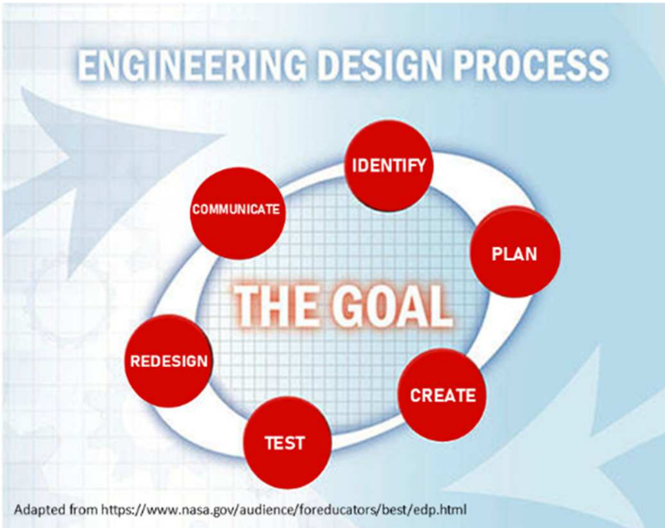

Fig. 1. A six-phase engineering design model

We examined the formal reports submitted by ten exceptional secondary students to a national engineering competition in the U.S. Each was reviewed for evidence of the student's engagement with each of the six phases of engineering design described here. We found that all the exhibits showed the students' abilities to create and test prototype solutions, but the formal reports varied widely in how well they displayed the student's ability to identify open-ended problems, plan their investigations, redesign multiple protypes based on their analyses, and make effective use of communication to invent new ideas early in projects and to take advantage of opportunities to collaborate during the project (see Table 1).

TABLE I. FEATURES OF STUDENT REPORTS BY DESIGN PHASE

Topic	Identify A. Multiple representations of problem B. Multiple solutions C. Possible Methods	Plan A. Design standards B. Project Standards C. Sketches or Diagrams	Create A. Methods B. Materials C. Division of Labor/Multiple models	Test A. Prototypes/Models (Hypotheses) B. Parameters/Constraints/Variables C. Record Keeping	Redesign A. Iterations/Users B. Analysis C. Evaluation	Communication A. Rhetorically pervasive B. Writing as Invention C. Evidence of Collaboration
Conserve Water	C	ABC	B	B	BC	BC
Disaster Proof Home	C	A	AB	AB	ABC	C
Voice Assisted H2O System	C	C	AB	AB	A	AC
Artificial Skin	BC	B	AB	AB	ABC	A
Hemp Bridges	B	AB	ABC	ABC	ABC	AC
3D Clinostat	BC	AB	AB	AB	A	AC
Shakey Wakey	ABC	A	AB	AB	C	C
Visually Impaired	C	B	AB	AB	B	A
Launch Vehicle	BC	AB	ABC	ABC	AB	AC
Fall Detection System	ABC	AB	AB	AB	ABC	AC

A. Identify and Define the Problem

Building on the work of Simon, we looked for evidence of how the students conceived of the ill-defined or open-ended problems they addressed, as well as the range of solutions they considered pursuing with their range of methods. This process of problem representation would probably best be reflected in a research notebook where students might feel free to include multiple sketches, rough diagrams, unanswered questions, unorganized notes from observations, or even recollections of things they had read or heard about related topics. Unfortunately, our access was limited to only the students' final reports. Consequently, the student's statement of the engineering design problem was often narrow and singular rather than open-ended and plural. Evidence of preliminary conversations with faculty mentors along with points of confusion or contradiction in the definition of problems were very seldom revealed.

For example, in a student report about artificial skin, the general goal was stated clearly, "to create a synthetic artificial skin that is flexible and capable of sensing temperature and pressure/touch." But then the focus in rapidly narrowed to citrus and apple-based pectins. If other materials were seriously considered as subjects for the study, no information is provided about those deliberations. In this case, a total of two solutions are compared, strengthening the author's claims for the superiority of apple-based pectin and more research in this area.

B. Plan for the Design and the Project

We read for evidence in the planning phase of student's abilities to establish clear design standards as well as broader project standards like project schedules and budgets. Multiple sketches might also reveal important shifts in the design thinking and planning. As with the problem identification phase, most of the planning phase would best be exhibited in a research notebook rather than in a formal report. Two students did append rough sketches of solution designs that were created in early phases of the project. Others presented plans and designs only in writing.

For example, one student designed a fall detection system for the elderly. After presenting a review of available systems, the student presented their design and project objectives and constraints as a table (see Table 2). While they did not quantify "low cost" or present any schedule for the design and development, it is clear that this student considered both design and project goals.

TABLE II. DESIGN OBJECTIVES

Constraints	Objectives
Maintain privacy	Embedded system
Work in the absence of light	Fall detection with high accuracy
Can call for help	Easy to use and robust
Low cost	Open source

C. *Create Prototypical Solutions with Specific Materials and Methods*

For evidence of this phase of the engineering design process, we looked for discussions of the methods and materials that the students employed, along with any division of labor that was involved in those methods. Of course, in formal reports, it is conventional to include specific sections that discuss methods and materials, and all of the students' reports did so. In some cases, the students also included some discussion of the collaboration required to conduct certain experiments or to obtain needed equipment, but this was not consistently the case.

In a report about typhoon resistant housing designs, a student relied upon wind tunnel and blown sugar methods of testing two prototype designs. The results were photographed and in the case of blown sugar, physically collected for measurement. In this case, the prototypes were provided by the "aid and generosity of the Building Momentum LLC in Alexandria, Virginia," with the assistance of "United States Marine Sean Flores . . . the main coordinator." The specific forms of collaboration are not made any clearer. Access to the student's research notebook may have been able to clarify the division of labor in creating the prototypes.

D. *Test the Prototype for Quality against Standards*

All of the student reports demonstrated their ability to test multiple prototypes or models against a set of design standards and to record and present the measured results. The reports did vary in how well the students identified the parameters, constraints, or variables that most affected the outcomes of the testing, and not all the reports included statements of formal hypotheses. The results of testing were most often presented in numerical tables, but some students included graphic or photographic test results as well.

One student who designed a voice-activated virtual assistant application for agriculture attempted to state a formal hypothesis about its ability to reduce water consumption and improve crop yields. He continued by noting the key constraints on the design, writing "To test the hypothesis, the application's algorithm will have to employ natural language processing techniques to extract inputs from the user, APIs to gather relevant data for calculation, and mathematical models and logic to compute the water requirements and growth stage. Additionally, the algorithm will determine specific growth stages and water requirements for cotton and corn crops." He concludes that ". . . the Google Test Simulator Results validate that the algorithm was able to properly capture the essential inputs from the farmer in a variety of languages, compute the final water requirements and growth stage, and relay the information in a speech response in the corresponding language."

E. *Redesign Based upon Analysis and Evaluation*

Each of the student reports exhibited the author's ability to redesign their prototype solution based on an analysis and evaluation of the testing results. They each indicated the number of trials, the users involved in the testing, and the criteria for analysis, evaluation, and redesign. In one case, 34 trials were represented in the student's report.

An example of the redesign phase was clearly presented in a report on the design of a rocket for reusable and autonomously landing suborbital launch. This student began by constructing his own rocket motors, but after repeated failures, learned that it "was not worth the time or effort." After initial drop tests of the new prototype failed, the student "designed and developed a novel 3D printed propulsion system" using four motors. But this proved difficult to control, so another version with a single motor was 3D printed and "integrated into a new vehicle." This report makes clear the value of iterative redesign based up data analysis and evaluation. In all, seven of ten projects involved iterative redesigns, and of those, the average number of redesigns per project was three (see Table 3). Each involved only the student investigator as the user of the redesign.

TABLE III. TABLE 3 NUMBER OF REDESIGN ITERATIONS & USERS

	Conserve Water	Disaster Proof Home	Voice Assisted H2O System	Artificial Skin	Hemp Bridges	3D Clinostat	Shakey Wakey	Visually Impaired	Launch Vehicle	Fall Detection System
Redesign Testing Iterations	-	2	4	9	2	2	-	-	3	2
Number of Users		1	1	1	1	1			1	1

F. *Communicate Persuasively throughout the Process*

Our review of the roles of communication in the engineering design processes of these secondary students was limited to the formal reports of their investigations. We did not have access to their research notebooks, the correspondence with their faculty mentors, or the comments of peer and faculty reviewers upon earlier drafts. Consequently, communication was reflected in the individually-authored student papers as simply equivalent to a "final" stage of the engineering design process, that is, reporting results at the conclusion of the investigation to a group of judges of a national engineering competition. This type of formal communication, along with oral presentations and perhaps research posters, is both expected and correct. But absent from this type of communication relative to engineering design is any clear reflection of the roles of discussion, sketching, and writing in the problem representation work that constitutes rhetorical invention, or any clear reflection of the iterative design process manifest through a series of progress reports, whether written or verbal. While in some cases the students' formal reports did acknowledge the collaboration of faculty mentors and other reviewers, debates or deliberations over multiple problem definitions and solution types are omitted in the formal reports. Instead of extended background discussions about the multi-faceted nature of the ill-defined problems that they addressed, the students' formal reports rhetorically moved very quickly toward narrow problem definitions that were described in quantifiable engineering terms only rather than in broader philosophical, ethical, or deliberative rhetorical terms that address what is best for a society.

For example, in a student's report about an improved method of creating ice bridges in the Alaskan winter to transport goods, no discussion is given to the social reliance upon truck transportation rather than, for instance rail transit, or to the effects of increased fossil fuel consumption with the improved bridge system, or to the effects of climate change upon the future reliability of ice structures, even in Alaska. Instead, the student writing defines the problem as how to reduce the time required to construct an ice bridge, assuming that the winter climate is a constant. "One of the methods people use to commute large amounts of materials across a river in Alaska is through the use of ice bridges, allowing commute [sic] during the winter. Currently, creating an ice bridge is a tedious task that require weeks, and in some cases, months to complete." Similarly, in the conclusion to this paper, the student makes a claim for the success of an improved, hemp rope-reinforced design, but does so only in terms of the measured strength of materials:

> *It is estimated that the maximum moment capacity from the added rope was 0.933 kip*ft/ft and the moment capacity from the added hemp fiber mat was 8.8 kip*ft/ft. The superposition of the two elements brings the total moment capacity of the reinforced ice section to 9.733 kip*ft/ft. This gives a factor of safety over the Moment of Forces from the FEA [Finite Element Analysis] model of 2.85.*

The student did not, however, consider materials other than hemp or attempt to quantify the time or labor saved by the hemp-reinforced construction method. The student provides little environmental context, mentioning only in passing that the environmental impacts of hemp fiber and rope upon bodies of water should be researched.

This student did acknowledge a number of collaborators in the investigation – his faculty mentor, two university faculty members who provided access to equipment, a sibling who participated in conducting the experiments, and his mother who reviewed the formal report.

While this student's engineering design formal report is conventional and rhetorically persuasive, in the sense that the hemp-reinforced bridge design was found to be stronger than ice alone, it, like almost all formal reports composed at the conclusion of the engineering design process, limits our perception of the roles that communication played in the invention stages of problem definition and in iterative redesign. The report does acknowledge the collaborative work that led to the report, but in very brief and superficial ways. And while this is conventional, research into the roles of communication in the engineering design process should incorporate reviews of student research notebooks, sketches and plans, email correspondence and meeting notes, progress reports, and other artifacts of the communication process.

III. Conclusion

Our review of this set of ten formal engineering design reports written by high-achieving secondary students for a national competition reveals the students' command of the conventional design phases of creating prototypes, testing, and redesigning based on an analysis of results. But it also shows that students may be less adept at identifying and defining open-ended problems in multiple ways and considering multiple methods before deciding upon a specific line of inquiry. Students may be quick to restate open-ended problems with social or environmental implications as narrower technical problems that can be more easily measured and quantified. Without a portfolio approach to student competitions, judges cannot see or evaluate student research notebooks that may include sketches, rough diagrams, unanswered questions, and full data sets that may include conflicting or contradictory observations. While each of these ten students submitted a persuasive report with a conventional organization, very few demonstrated a full command of all six phases of the engineering design process. Their abilities to communicate effectively with faculty mentors, collaborators, and reviewers are merely hinted at in the brief acknowledgment sections included in eight of ten reports. We argue for the collection and review of project portfolios for engineering design students, portfolios that may more fully reveal their inventive abilities in each phase, and deepen the value students assign to the engineering design process. A rich multi-media collection of the work across a design project also helps students think in terms of a professional portfolio that can be linked to on a resume, connected to future research funding requests, and pointed to for claims of intellectual accomplishment. We will expand upon this research by collecting and analyzing exhibits from future engineering design competitions.

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