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High School Engineering Class: From Wood Shop to Advanced Manufacturing

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High School Engineering Class: From Wood Shop to Advanced Manufacturing (Evaluation)

Abstract

The maker movements, a general term for the rise of inventing, designing, and tinkering, and the addition of engineering standards to the Next Generation Science Standards (NGSS) have spawned a major evolution in technology classes throughout the country. At Georgia Institute of Technology, a new curriculum attempts to bring the maker movement to high school audiences through both curricular and extra-curricular channels. The curriculum is structured around engineering standards and learning goals that reflect design and advanced manufacturing content, along with employability skills, while borrowing best practices from 'wood shop' and 'technology education' classes. The hope is that this course will bolster many of the 'Attributes of Engineers in 2020' described by the National Academy of Engineering and 21st Century Skills—these skills and attributes can be beneficial to any college or career path, not just one in engineering. The course incorporates design-build activities into entrepreneurial and business contexts, providing relevance to foundational math skills and science practices while integrating problem solving and cutting-edge technology. The course requires that students draw and render design concepts, communicate design concepts to their peers and clients, fabricate design artifacts, and document their requirements and decisions while engaging in the engineering design process.

The purpose of this paper is to explore the results from the first and second year implementation of a maker-infused Advanced Manufacturing (AM) course for high school students in a low income, rural-fringe school system. Results from a portfolio assessment and 21st Century Skills surveys will be discussed in terms of course effectiveness and challenges to implementation. Similarities and differences between learning goals for this new AM course and the more traditional wood shop and technology education classes will be highlighted. Implications for engineering education, theory, and practice are discussed.

Introduction

Technology evolves rapidly, as do the jobs associated with it. Gone are the old-fashioned assembly lines where simple, repetitive manual labor was all that was required; with robotics and automation, the future of manufacturing demands a workforce that is flexible, adaptable, and adept at solving problems. According to a study by the Deloitte Manufacturing Institute, a shortage of skilled production workers (e.g. machinists, technicians, operators, etc.) is having a negative impact on productivity in the manufacturing sector. In particular, the study notes that the national education curriculum is inadequate for producing the skilled workers required to fill these jobs [1]. In moving away from the historically vocational classes at the high school level, many schools have done away with ‘wood shop’ and other hands-on courses, but the need for workers with design-build skills has not disappeared along with these courses [2].

While Science, Technology, Engineering, and Mathematics (STEM) are recognized as important areas for growth due to demand for skilled workers in these areas, there are many challenges associated with creating a truly integrated STEM course at the high school level that is relevant, authentic, and flexible enough to be taught to students of varying skills and career aspirations.

A new, introductory advanced manufacturing high school course is being developed as part of a National Science Foundation Math Science Partnership at Georgia Institute of Technology with the intention of fostering design-build skills, 21st Century skills, and employability skills. The partnership is called Advanced Manufacturing and Prototyping Integrated to Unlock Potential, or AMP-IT-UP. It attempts to marry the best aspects of woodshop and technology education courses with contextualization and problem solving skills suitable for career-readiness. The course is being piloted in a ‘typical’ classroom in a rural-fringe area where there is a need for skilled labor. The course is designed to be appropriate for all students, including those who are college-bound, those pursuing a two-year degree, and those who will seek employment immediately after graduation.

There are two main contributions of this paper. The first is to describe a new high school engineering course that incorporates design-build activities into entrepreneurial and business contexts, thereby providing relevance to foundational math skills and science practices while integrating problem solving and cutting-edge technology. The second is to explore evaluation results from the first and second year implementation of this course for high school students in a low income, rural-fringe school system. The evaluation utilizes a mixed-methods approach, employing both qualitative and quantitative data sources to explore the effectiveness of the course on increasing student learning and 21st Century skills [3]. Data are derived from a portfolio assessment and a 21st Century skills survey. The engineering design portfolio assessment (EDPA) includes an electronic log to document students’ progress through the stages of the engineering design process. The survey is designed to measure critical thinking, leadership, communication, and collaboration, and teamwork.

Background: The Maker Movement and High School Technology Education

The ‘maker movement’ is defined by Adweek as the umbrella term for independent inventors, designers, and tinkerers [4], and is viewed by Time magazine as a driver for innovation [5]. This movement, which started in the 1990’s, embodies a reversion from the theoretical to the practical, using one’s hands to physically make and build things for the purpose of solving new problems, solving old problems, creating art, or becoming intimately familiar with a particular technology. The movement was likely spurred by the introduction of inexpensive 3D printers and microcontrollers and has continued to grow through popular press, including Make magazine [6], Instructables [7], and other websites featuring how-to articles for getting started. Universities are embracing this movement and developing on-campus maker spaces chock full of prototyping equipment to infuse their theory-rich curricula with real applications to develop the next generation of problem solvers [8-10], and this trend is trickling down into K-12 education as well.

High school and university engineering curricula in the US have been following similar trajectories for some time. In the early 1900's, engineering was treated more as a 'trade' at the university level, and high schools encouraged vocational studies, including auto repair, wood shop, metalworking, cosmetology and other 'trades' to the non-college bound. Between 1935 and 1965, most university engineering curriculum moved away from a trade-school curriculum to a more theoretical, mathematically-intensive one, delaying any hands-on design projects until the senior or 'capstone' design course [11].

Similarly, the nation's high schools tried to erase the division between the trades and the college-preparatory tracks to prepare anyone who might be inclined to attend a university. As early as the 1980's, educational researchers began demanding changes to the wood shop and industrial arts curricula to place a heavier emphasis on problem solving [12]. In Georgia, the two-track system was recommended for elimination in 2003 and began disappearing shortly thereafter [13]. As this division between vocational and college preparatory tracking disappeared, so did many of the auto shops, wood shops, and metalworking shops at the nation's high schools.

In some schools and school districts, 'technology education' courses took the place of wood shop and industrial arts courses. In the 1990's and 2000's, many of the technology courses involved 'high-tech' modules, or stations throughout the classroom, that allowed the students to move through self-paced lessons requiring little teacher involvement [14]. The classroom was divided into independent work stations, and each station had its own workbook, assessments, instructions, computer, multi-media, books, and associated experimental apparatus. In this way, student groups might all be working on different projects [15]. While students in these courses gained exposure to many different technologies and possible career tracks, most of the work was highly prescriptive with little room for innovation. This type of course format neglects the need for iteration when designing a solution to a problem. In addition, the equipment for the modules becomes outdated quickly, and there is a certain irony in teaching a technology class using outdated technology.

With the recent reversion back to making and hands-on learning, high schools are facing the challenge of reinventing the class formerly known as shop, or industrial arts, to meet the needs of a 21st century workforce. Currently, there are other updated approaches to high school technology education, often rebranded as engineering or STEM courses, including Project Lead the Way [16] and Engineering by Design [17]. The Project Lead the Way Introduction to Engineering Design course presents some of the same concepts as the AM course introduced in this paper, including the design process and engineering notebook. Engineering by Design is centered on technology literacy, and shares many of the same goals with respect to cultivating the next generation of innovators.

Advanced Manufacturing Course Development

There are three primary strands that are interwoven in the AM course content: the engineering design process, building and manufacturing skills, and entrepreneurial thinking. The course is comprised of several multi-week project units, interspersed with some shorter skill-building units. Most projects in the course require the use of the design process, which we define in Figure 1. There are many published versions of the design process and no one model is generally accepted, but the overarching concepts are consistent between university engineering courses [18], other high school engineering courses [19], and the Next Generation Science Standards (NGSS) [20]. This course does not focus on the specific sequence or semantics of the process but rather on using the process in practice and understanding its systematic, iterative nature. Students are required to carefully document their ideas and data collected throughout the design process in a digital Engineering Design Process (EDP) log, which is assessed after each project using a rubric (described below). In addition, students must verbally communicate with their peers and teacher in both formal and informal presentations to justify their design decisions and pitch their final design solutions.

The building and manufacturing aspects of the course require the students to draw their ideas in two dimensions and fabricate them in three dimensions. Specifically, they must learn to communicate their ideas using both a pencil and a computer, and to prototype their design concepts using hand tools, power tools, and computer-controlled or 'advanced' prototyping technologies including the laser cutter, vinyl cutter, and 3D printer. The sequence of projects is such that there is logical progression from 2D to 3D, as well as a progression of sophistication in prototyping technology. Early in the course, students learn to use 2D drawing software such as Inkscape, a free program that can be used to create designs for both the vinyl cutter (for stickers) and the laser cutter [21]. As projects progress, students move to 3D CAD packages (such as IronCAD [22] or Solidworks [23]) to create blueprints for 3D objects and assemblies or to 3D print their prototypes.

Each of the course projects is framed as an appropriately contextualized design problem, and the projects are presented in order of increasing sophistication. The importance of considering your customer and market before designing a product is emphasized. For example, one of the first projects in the course is to build a portfolio to hold classwork in; in this case, the student is his or her own client. In the second project, the students are asked to design and build a birdhouse for a local bird species, and the bird functions as the customer. The students must research the bird's needs as part of the 'Understand' step in the design process and build a house that meets those requirements. As the projects grow more sophisticated, students are paired with local businesses or school clubs for whom they will design their prototypes. For the final project, students must consider product families, customization, and mass-market strategies, as well as cost considerations related to prototyping and manufacturing.

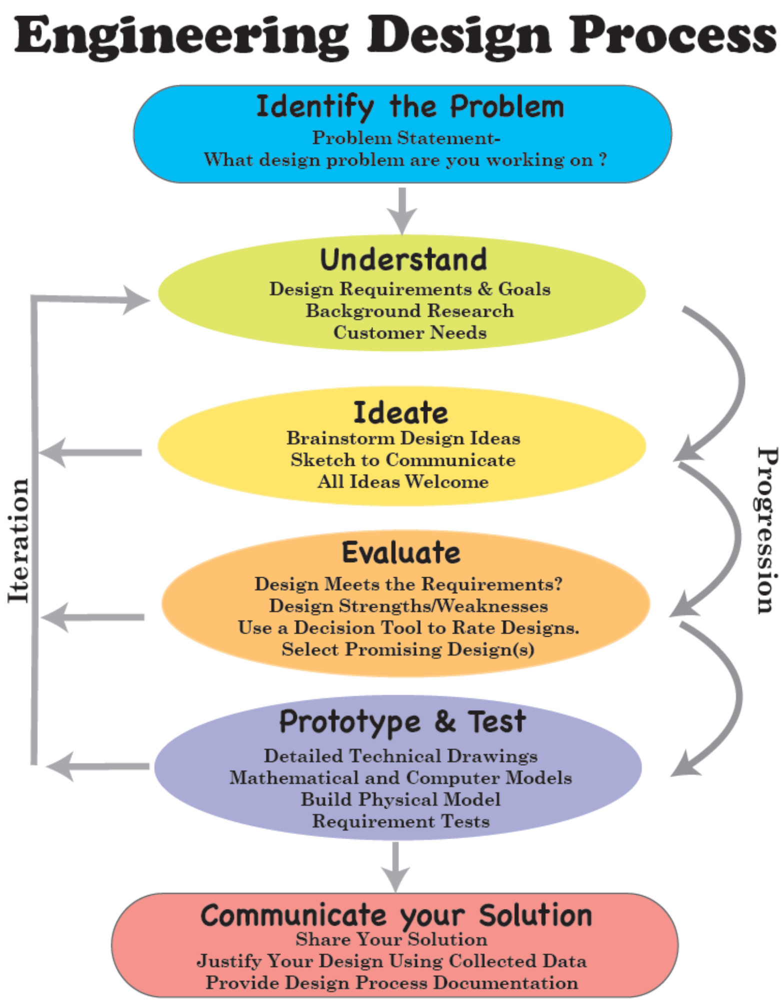

Figure 1: Engineering Design Process

In conjunction with the primary strands (design process, manufacturing, entrepreneurial thinking), math and science skills are used to enhance the quality of the projects and the associated data analysis. For example, constraints on material area or perimeter may be provided, and students have to prove that their design concepts do not violate these constraints prior to prototyping. Thus, students are required to use measurement, calculation, and estimation in context to show that their design is feasible. It is this integration and contextualization which makes this course truly a STEM course—the students apply skills from science and math to engineer solutions and apply different technologies to build those solutions.

Based on the course learning strands described above, the initial (measurable) learning goals developed for the course are the following:

1. Students create sketches, drawings, and builds to understand the connection between visual representations and actual design artifacts.

2. Students measure, cut, form, fasten and finish using hand and power tools to fabricate an artifact.
3. Students sketch, dimension, visualize, render and verify with advanced manufacturing tools and software to fabricate artifacts.
4. Students conduct research and document design requirements to develop a design specification.
5. Students iteratively document, communicate and evaluate design concepts to identify feasible solutions for a design problem.
6. Students design and implement tests to determine how well design artifacts meet the design requirements.
7. Students collect, analyze and interpret data using appropriate mathematics to make informed, rational decisions.
8. Students present all documentation, data, and design artifacts to illustrate understanding of the engineering design process.
9. Students present relevant documentation, data, and design artifacts to pitch their design solutions to different audiences.
10. Students evaluate their own design solutions with respect to their design specifications and identify critical decision nodes in the design process to understand the systematic, iterative nature of design.

It is important to note that the learning goals are not tool-specific as they might be for a woodshop or metalworking course, where the focus is on fabrication rather than on design or problem solving. In addition, the same course content could be delivered using any number of different project ideas, leaving room for instructor creativity. The course is about using tools to solve problems with the understanding that flexibility and innovation are key attributes in the work force. This course seeks to retain the satisfaction of 'do-it-yourself' that seemed to be prevalent in the industrial arts, while incorporating cutting-edge technologies and more general problem solving skills to solve design problems. Our intent is that the course will foster innovation, communication, teamwork, foundational math skills, and other 21st century skills needed in the workforce.

Assessment

As engineering-related concepts and the engineering design process become more prominent in K-12 curricula, a critical need simultaneously arises for assessment methodologies in this content area [24]. Many engineering education researchers have recognized challenges associated with assessing the engineering design process and noted that further research and developments in this area are needed [24-28]. Researchers as recently as 2014 stated that, upon undertaking a project to determine competency levels for engineering processes and skills (which they began in 2011), "no generalized assessment tools existed that could be used to benchmark and score student work in engineering design" [27]. Standardized assessments of content knowledge and skills similar to state-wide assessments or SAT's have yet to be developed for engineering achievement at the K-12 level, and even if they existed, may not appropriately capture the decisions and creativity that go along with engineering design.

Engineering design process instruction and student activities are often complex, build on earlier instruction, benefit from multiple iterations, and cover multiple learning domains. As such, they are ideally evaluated with an assessment strategy that is largely performance-based, including some pre-and post-test measurements, both formative and summative data, and both quantitative and qualitative data [25, 26, 28].

Existing performance-based assessment methodologies focus on evaluation of student work (e.g., student portfolios, engineering notebooks or logs, individual or group presentations) [24, 25, 28, 29], and have also included efforts to assess student attitudes via self-report questionnaires [30]. These assessments tend to be primarily qualitative and subjective, although efforts to increase the objectivity of such assessments have been made with the introduction and validation of the Engineering Design Process Portfolio Scoring Rubric (EDPPSR) [25, 27], a set of standardized rubrics for evaluating learning outcomes of the engineering design process. A modification of the EDPPSR was used for the evaluation in the current study, discussed in more detail in the Evaluation section below.

Evaluation and Methodology

This evaluation research utilizes a mixed-methods approach employing both qualitative and quantitative data sources to determine the impact of the curriculum on student learning and 21st century skills. Mixed methods designs are methodologically superior to simpler designs because they allow for triangulation of data and the ability to leverage the strengths of several different methods [31]. Consistent data from both qualitative and quantitative methods increases the trustworthiness of findings, while inconsistency of data across methods calls into question the validity of the findings [32]. The following evaluation research questions guided the study:

1- What changes do students report, based on the new classroom practices in the areas of 21st century skills such as problem solving, communication and collaboration, and teamwork?
2- What is the impact of the new curriculum on student learning?

Sample and Data Collection

Two cohorts of high school students participated in the study. The first cohort consisted of ninth graders (n=10), predominantly African American and male students. The engineering classes are year-long; therefore, the 21st century survey was administered to the first cohort at the beginning and at the end of the school year (2013-2014). The second cohort consisted of eleventh graders (n=24), mostly males and with a fairly even distribution of Caucasian and African American students. The engineering design portfolio assessment was only implemented in the second cohort classes in the current academic year (2014-2015). The pre 21st Century survey was also administered at the beginning of the current academic year. The post survey will be administered in May 2015, and will be analyzed for presenting at the conference.

Data Sources

Data for this study were collected using two major instruments: an affective survey made up of rating scale items to assess student attitudes related to 21st Century Skills including critical thinking, leadership, communication, and collaboration, and teamwork, and an engineering design portfolio assessment to measure student learning.

Affective assessment. The survey items were adapted and modified from several validated instruments related to the 21st Century Skills listed above [33, 34]. In addition to 21st Century Skills, student engagement and self- efficacy were also measured. This instrument, developed by researchers at Georgia Tech for this project, included forty-five items on a 5-point Likert-type rating scale (e.g., ranging from “Strongly Agree” to Strongly Disagree”), with a Cronbach’s α of 0.91, and internal consistency for each of the five scales ranging from 0.84 to 0.95.

Engineering design portfolio assessment. In addition to affective data, student achievement data were collected using an engineering design portfolio assessment (EDPA). For each project, students used a digital log to document their progress through the stages of the engineering design process (see Figure 1). Specifically, an electronic template for the portfolio was provided in the form of a Google Sheet (spreadsheet) with pages that correspond to stages of the EDP. As students completed their design project, they used the online portfolio to document their work by entering text and uploading pictures. The online format of the design process log facilitated data collection and scoring (described below).

Scoring rubric. Student portfolios for each project were assessed using a scoring rubric made up of elements (i.e., rubric domains) that correspond to the stages of the design process used in the curriculum. The rubric for the EDPA was adapted from the Engineering Design Process Portfolio Scoring Rubric [35]. The EDPPSR was developed as part of a National Science Foundation (NSF) grant whose purpose was to develop a scoring system that could be used to distinguish among student performance levels on engineering design projects [36]. The rubric is currently used as the end-of-course assessment for the capstone Engineering Design and Development (EDD) course from Project Lead the Way [37]. Additional details about the history of the original EDPPSR instrument are provided by Goldberg (2014).

The EDPPSR was revised in order to obtain an instrument that is aligned with the AMP-IT-UP high school curriculum and is appropriate for describing student achievement at the high school level. Whereas the original EDPPSR included 14 individual scoring elements, the rubric for the EDPA includes eight elements that correspond to the stages of the design process used in the course: A) Identify the Problem; B) Understand; C) Ideate; D) Evaluate; E) Prototype and Test; F) Iteration; G) Progression; and H) Communicate your Solution. Each element was scored using a rating scale with six categories (5 = Exemplary; 4 = Advanced; 3 = Proficient; 2 = Developing; 1 = Novice; 0 = No evidence). The performance level descriptors for elements A through G were adapted from similar elements in the original instrument. The performance level descriptors for element H (Communicate your Solution) were developed in collaboration with the current high school instructor for the high school course. In order to facilitate completion of the log and understanding of the scoring scheme, students were provided with a checklist that highlighted the major components of the project on which their work would be evaluated. Appendix A includes the scoring rubric and student checklist for the EDPA.

After students completed the engineering design process log, their work was evaluated using the scoring rubric for the EDPA. A member of the research team scored the process logs. Because the researcher was not present during student presentations, scores were only assigned for elements A through G of the EDPA rubric.

Results and Discussion

For cohort one, student survey results showed very little or no gain between pre and post, except the teamwork, which is measured through communication & collaboration and cooperation subscale and engagement. Student survey results indicated noticeable gains in *communication & collaboration and cooperation*. Students' average ratings were between 2.0 and 3.0 on the scale in the pre survey, and rose above 4.0 in the post survey for both *communication & collaboration and cooperation*. There was also a noticeable change in terms of student engagement. The average rating of student engagement was little below 3 (midpoint) at the pre survey, and 4.5 in the post surveys. For cohort one, the portfolio assessment was attempted using paper portfolios (before the development of the EDP Log) and almost no usable data could be retrieved. Cohort 1 consisted of ninth graders who had not had exposure to an engineering curriculum in middle school, so there were many challenges to implementing something as sophisticated and self-driven as an engineering design notebook. Without much scaffolding and the requirement of the students keeping their own work organized, it is very difficult for a researcher to evaluate student learning using classroom artifacts. Based on our preliminary observations, this type of performance-based evaluation system is highly dependent on students' *ability* and *willingness* to document their thought processes, ideas, strategies, drawings, requirements, etc. as they move through the engineering design process. If their movement through this process is insufficiently or poorly documented, results from this type of assessment may not be meaningful. In technology classes that have traditionally required little to no written documentation, this type of paradigm shift is difficult to enact in practice. To better scaffold this process, the EDP log was introduced for cohort two.

For cohort two, the EDP log was implemented, and students have begun to use it as part of their engineering design projects. The log requires careful documentation of requirements (which then automatically populate throughout the workbook) and active updating of those requirements as prototypes are tested and as any new information about the problem is acquired. In addition, students are expected to generate multiple candidate solutions; this is challenging to implement, even at the collegiate level, due to design fixation [38]. While much more useful data was gained from scoring the EDP logs, the assessment of student learning is still heavily relying on students' abilities to document their decisions in an organized and meticulous way. Successful implementation of the EDP logs or any other engineering notebook or portfolio is also dependent on the teacher and his or her willingness and interest in enforcing documentation of the design process. If the teacher is used to the fabrication-focused learning goals of shop class or the easily-graded multiple choice assessments from the technology modules, this documentation and associated grading can be a difficult shift.

The results from the EDP log scoring are shown in Table 1, below. The results indicate the need for additional improvements to the log and rubric, as well as better student understanding of how to use the log. The highest score achieved by any student in any category was 4 out of 5, with many more being 2 or 3 (developing or proficient.) Many students did not complete the log or filled out only minimal information and so received a score of zero.

Because engineering courses are being implemented at the middle school level in this district as well, the hope is that future cohorts of ninth graders will grow accustomed to the expected documentation, as the same EDP log is used in the middle schools. This should lead to more meaningful data capture.

Table 1. *Portfolio Ratings: Descriptive Statistics*

Element*	*Mean*	*SD*	*Range (Min, Max)*
A: Identify the problem	1.25	0.94	(0, 3)
B: Understand	1.17	0.76	(0, 3)
C: Ideate	1.21	0.83	(0, 3)
D: Evaluate	1.21	1.06	(0, 4)
E: Prototype & test	1.00	0.88	(0, 2)
F: Iterate	0.67	0.82	(0, 2)
G: Progression	0.63	0.58	(0, 2)

* Element H: Communicate your solution was not scored.

Conclusions and Future Work

An advanced manufacturing course may be the next evolutionary step for the industrial arts and technology education curriculum at the high school level. While this course is only in its pilot stage, we believe that the learning goals developed for the course and the primary course strands (design process, manufacturing, entrepreneurial thinking) will begin to close the skills gap identified by the manufacturing sector in the US. The course is versatile enough to be relevant for college-bound students as well as those seeking employment immediately after high school graduation. While the course content has similarities with other engineering and technology courses developed for high school classrooms, this course is unique in its emphasis on contextualization and entrepreneurial thinking skills, which are applicable in any domain.

Major challenges exist in the area of assessment of student learning with respect to the learning goals. The course, design process logs, and rubrics will continue to be updated based on teacher feedback, classroom observations, and student artifacts. The use of electronic data has improved research efforts; however, there is still room for improvement in collecting and assessing student work and framing the design problems in a way that necessitate rigorous documentation.

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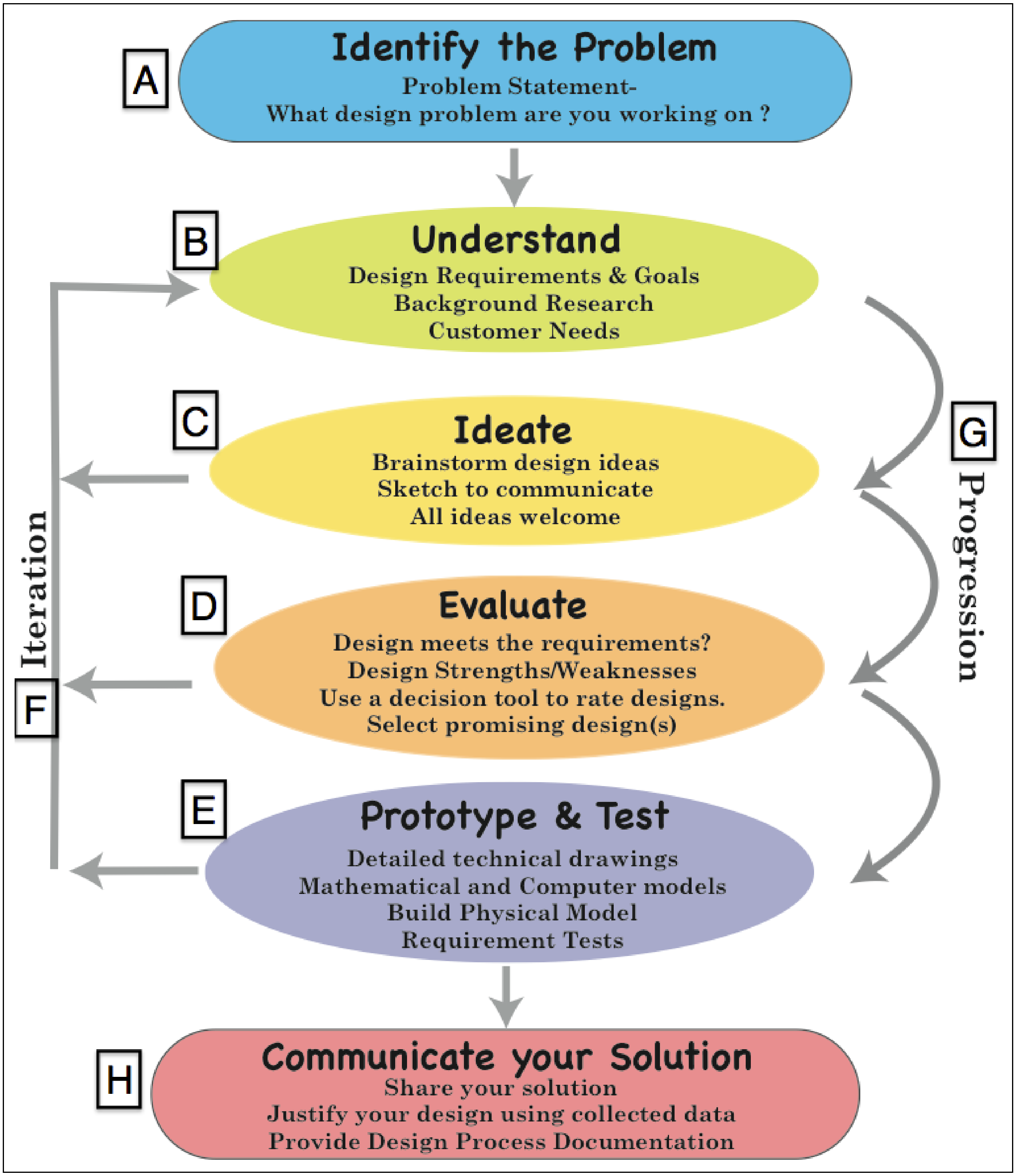
Appendix A

Engineering Design Process Rubric:



Element A: **Identify the Problem**

Score Point	Performance Level	Performance Level Description
5	*Exemplary*	The problem is **clearly and objectively** identified and defined with **considerable depth**, and it is **well elaborated with specific detail**.
4	*Advanced*	The problem is **clearly and objectively identified** and defined with **some depth**, and it is **generally elaborated with specific detail**.
3	*Proficient*	The problem is **somewhat clearly and objectively** identified and defined with **adequate depth**, and it is **sometimes elaborated with specific detai**l, although some information intended as elaboration may be imprecise or general.
2	*Developing*	The problem is identified **only somewhat clearly and/or objectively** and defined in a **manner that is somewhat superficial and/or minimally elaborated** with specific detail.
1	*Novice*	The identification and/or definition of the problem is **unclear, is unelaborated, and/or is clearly subjective.**
0	*No Evidence*	The identification and/or definition of the problem are **missing** OR **cannot be inferred** from information included.

Student Checklist:

• I described the exact problem clearly.	
• My description of the problem is not biased toward any one solution.	
• My description of the problem includes information about the background, context, or setting for the problem.	

Element B: **Understand**

Score Point	Performance Level	Performance Level Description
5	*Exemplary*	Design requirements are **listed with dates** that indicate when they were added to the list along with an **appropriate source**. The requirements are **consistently clear and detailed, objective, measurable**, and they would be **highly likely to lead to a tangible and viable solution** to the problem identified; there is evidence that requirements represent the needs of the client or customer. The sources for the requirements are logical and include evidence of market research as well as testing of initial prototypes.
4	*Advanced*	Design requirements are **listed with dates** that indicate when they were added to the list along with an **appropriate source**. The requirements are **generally clear and detailed, nearly always objective and measurable**, and they would be **likely to lead to a tangible and viable solution** to the problem identified; there is evidence that requirements represent the needs of the client or customer. The sources for the requirements are logical and **generally include evidence** of market research and testing of initial prototypes.
3	*Proficient*	Design requirements are **listed with dates** that indicate when they were added to the list , and generally include an **appropriate source**. The requirements are **generally clear and somewhat detailed**, **generally objective and measurable**, and they have the **potential to lead to a tangible and viable solution** to the problem identified. There is evidence that requirements represent the needs of the client or customer. The sources for the requirements are logical, and **at least a few include evidence** of market research and testing of initial prototypes.
2	*Developing*	Design requirements are **listed with dates** that indicate when they were added to the list along with sources for most of the requirements. **Some/all of these requirements may be incomplete and/or lack specificity**; these design requirements may be only **sometimes objective and/or measurable**, and it is **not clear that they will lead to a tangible and viable solution** to the problem identified. There is evidence that the requirements represent the needs of the client or customer. The sources for the requirements may be **insufficient, outdated, or of dubious credibility.** There may not be evidence of market research and testing of initial prototypes.
1	*Novice*	**An attempt is made to list, format, and document** research for requirements, but these generally do not include sources. The requirements may be **partial and/or overly general, making them insufficiently measurable to support a viable solution** to the problem identified. There is **no evidence** that the requirements represent the needs of, or the client or customer. The sources for the requirements are **overly general, outdated, and/or of dubious credibility.** There is no evidence of market research or testing of initial prototypes.
0	*No Evidence*	Design requirements are either **not presented or are too vague** to be used to outline the measurable attributes of a possible design solution to the problem identified. Documentation of research to support the requirements do not include sources, and is **essentially only the opinion of the researcher.** There is no evidence of market research or testing of initial prototypes.

Student checklist:

• I listed a set of design requirements (measureable things that a new design would have to accomplish in order to be seen as a real solution).	
• I indicated the date on which each design requirement was added to the list.	
• I described the research that I conducted for each design requirement. For example, this might include Internet research or market research.	
• I included a source for each design requirement.	

Element C: **Ideate**

Score Point	Performance Level	Performance Level Description
5	*Exemplary*	The process for generating possible design solutions was **comprehensive, iterative, and consistently defensible**, making a viable and well-justified design **highly likely. Multiple sketches** for potential solutions were provided; the **sketches were comprehensive and consistently provided sufficient detail** to communicate each design.
4	*Advanced*	The process for generating possible design solutions was **thorough, iterative, and generally defensible**, making a viable design **likely**. **Multiple sketches** for potential solutions were provided; the sketches were t**horough and generally provided sufficient detail** to communicate each design.
3	*Proficient*	The process for generating possible design solutions was **adequate and generally iterative and defensible**, making a viable design **possible**. **Multiple sketches** for potential solutions were provided; the sketches provided a**dequate detail** to communicate each design.
2	*Developing*	The process for generating a possible design solution was **partial or overly general and only somewhat iterative and/or defensible**, raising **issues with the viability** of the design solution chosen. **One or more sketch** for potential solutions was provided; the sketches were **general and provided partial details** about each design.
1	*Novice*	The process for generating a possible design solution was **incomplete and was only minimally iterative and/or defensible**. **One or more sketch** for a potential solution may have been provided and/or the sketches included **insufficient detail to communicate each design.**
0	*No Evidence*	There is **no evidence of an attempt to arrive at a design solution through an iterative process based on design requirements**. **No sketches** for potential solutions were provided.

Student checklist:

• I described the brainstorming and idea generation techniques that I used to help define possible solutions.	
• I sketched multiple potential solutions.	
• My sketches provided sufficient detail to communicate each design.	

Element D: Evaluate

Score Point	Performance Level	Performance Level Description
5	*Exemplary*	Students used a decision tool to rate each of their potential design solutions. The process for comparing possible designs solutions based on strengths and weaknesses was comprehensive, iterative, and consistently defensible. The design solution ultimately chosen was well justified and demonstrated attention **to all design requirements.**
4	*Advanced*	Students used a decision tool to rate each of their potential design solutions. The process for comparing possible designs solutions based on strengths and weaknesses was thorough, iterative, and generally defensible. The design solution chosen was justified and demonstrated attention **to most if not all** design requirements.
3	*Proficient*	Students used a decision tool to rate each of their potential design solutions. The process for comparing possible designs solutions based on strengths and weaknesses was thorough, iterative, and generally defensible. The choice of design solution was explained with reference to **at least some** design requirements.
2	*Developing*	Students may have used a decision tool to rate each of their potential design solutions. The process for generating a possible design solution was partial or overly general and only somewhat iterative and/or defensible, raising issues with the viability of the design solution chosen; that solution was **not sufficiently explained** with reference to design requirements.
1	*Novice*	The proposed design was superficially reviewed based on one or two considerations. The choice of design solution **lacked support related** to design requirements.
0	*No Evidence*	There is **no evidence provided** that a design solution was reviewed through an iterative process based on design requirements.

Student checklist:

• I showed that each of my possible solutions met the design requirements.	
• I described the strengths and weaknesses of each design.	
• I used a decision tool to rate the designs.	
• I described the solution that I decided to test, and described why I thought it was the best one to try.	

Element E: **Prototyping and Testing**

Score Point	Performance Level	Performance Level Description
5	*Exemplary*	The final prototype iteration is **clearly and fully explained** and is constructed with enough detail to assure that **all or nearly all design requirements** could be tested. A **well-supported justification** is provided for the requirements that cannot be tested or modeled mathematically and thus require expert review or further prototyping that is not currently feasible.
4	*Advanced*	The final prototype iteration is **clearly and adequately explained** and is constructed with enough detail to assure that **many design requirements** could be tested. A **generally supported justification** is provided for the requirements that cannot be tested or modeled mathematically and thus require expert review or further prototyping that is not currently feasible.
3	*Proficient*	The final prototype iteration is **clearly and adequately explained** and is constructed with enough detail to assure that **some design requirements** could be tested. An **adequately supported justification** is provided for the requirements that cannot be tested or modeled mathematically and thus require expert review or further prototyping that is not currently feasible.
2	*Developing*	The final prototype iteration is **explained only somewhat clearly** and/or completely and is constructed with enough detail to assure that **at least a few design requirements** could be tested. **There may be insufficient justification** for the requirements that cannot be tested or modeled mathematically and thus require expert review or further prototyping that is not currently feasible.
1	*Novice*	The final prototype iteration is **only minimally explained** and/or is not constructed with enough detail to assure that objective data on **at least one design requirement** could be determined. **Any attempt at justification** for the requirements that cannot be tested or modeled mathematically and thus require expert review or further prototyping that is not currently feasible **is missing**.
0	*No Evidence*	Any attempt to explain the final prototype iteration is **unclear or is missing** altogether. There is **no evidence that the prototype would facilitate testing** by suitable means for any of the design requirements.

Student checklist:

• I created detailed technical drawings for my solution.	
• Where possible, I created mathematical and computer models for the solution.	
• I built a physical model of my solution.	
• I showed that my design meets all of the design requirements.	

Element F: **Iteration**

Score Point	Performance Level	Performance Level Description
5	*Exemplary*	The project designer **provides a consistently clear, insightful, and comprehensive reflection** on, and value judgment of, **each major step in the project**; the reflection **includes a substantive summary of lessons** learned that would be **clearly useful** to others attempting the same or similar project.
4	*Advanced*	The project designer **provides a clear, insightful and well-developed reflection** on, and value judgment of, **each major step in the project**; the reflection **includes a summary of lessons** learned that would be **clearly useful** to others attempting the same or similar project.
3	*Proficient*	The project designer **provides a generally clear and insightful, adequately-developed reflection** on, and value judgment of, **major steps** in the project, although one or two steps may be addressed in a more cursory manner; the reflection **includes a summary of lessons** learned, **at least most of which** would be **useful** to others attempting the same or similar project.
2	*Developing*	The project designer provides a **generally clear, at least somewhat insightful**, and **partially developed reflection** on, and value judgment of, **most if not all** of the major steps in the project; the reflection i**ncludes some lessons learned** which would be **useful** to others attempting the same or similar project.
1	*Novice*	The project designer **provides a reflection** on, and value judgment of, **at least some** of the major steps in the project, although the **reflection may be partial**, overly-general and/or superficial; the reflection **includes a few lessons** learned of which at least one would be **useful** to others attempting the same or similar project.
0	*No Evidence*	The project designer **attempts a reflection** on, and value judgment of, at least one or two of the major steps in the project, although the **reflection may be minimal**, unclear, and/or extremely superficial; **any lessons learned are unclear** and/or of **no likely use to** others attempting the same or similar project; OR there is **no evidence of a reflection and/or lessons learned.**

Student checklist:

• I wrote a reflection about my design process for this problem.	
• My reflection describes the decisions I made and why I made them.	
• My reflection describes what I would do differently if I tried to address the problem again, or advice that I would give to someone else who was trying to address the problem.	

Element G: **Progression**

Score Point	Performance Level	Performance Level Description
5	*Exemplary*	The portfolio provides **consistently clear, detailed, and extensive documentation** of the design process and project that would with **certainty facilitate subsequent replication** and refinement by the designer(s) and/or others; attention to audience and purpose was **abundantly evident** in the choice of mode(s) of presentation, professionalism of style and tone, and the variety, quality, and suitability of supporting materials.
4	*Advanced*	The portfolio provides **clear, generally detailed and thorough documentation** of the design process and project that would be **likely to facilitate subsequent replication** and refinement by the designer(s) and/or others; attention to audience and purpose was **evident** in the choice of mode(s) of presentation, professionalism of style and tone, and the variety, quality, and suitability of supporting materials.
3	*Proficient*	The portfolio provides **generally clear and thorough documentation** of the design process and project that would be **likely to facilitate subsequent replication** and refinement by the designer(s) and/or others, although there may be some minor omissions or inconsistencies; attention to audience and purpose was **generally—but not always--evident** in the choice of mode(s) of presentation, professionalism of style and tone, and the variety, quality, and suitability of supporting materials.
2	*Developing*	The portfolio provides **partial or sometimes overly general documentation** of the design process and project that would be **likely to facilitate subsequent replication** and refinement by the designer(s) and/or others; attention to audience and purpose was only **sometimes/somewhat evident** in the choice of mode(s) of presentation, professionalism of style and tone, and the variety, quality, and suitability of supporting materials.
1	*Novice*	The portfolio provides **minimal documentation** of the design process and project that would be **likely to facilitate subsequent replication** and refinement by the designer(s) and/or others; attention to audience and purpose was **rarely evident** in the choice of mode(s) of presentation, professionalism of style and tone, and the variety, quality, and suitability of supporting materials.
0	*No Evidence*	The portfolio **attempts to document** the design process and project but **little/none of that information supports subsequent replication** and refinement by the designer(s) and/or others; **little/no attention to audience and purpose was evident** in the choice of mode(s) of presentation, professionalism of style and tone, or the variety, quality, and suitability of any supporting materials included.

Student checklist:

• My portfolio includes relevant documentation of each stage of the design process.	
• My portfolio provides enough detail to guide someone else in following my procedure.	

Element H:* Communicate your Solution

Score Point	Performance Level	Performance Level Description
5	*Exemplary*	Presentation communicates the topic in clear and compelling manner. Presentation exhibits expertise in content and method of production.
4	*Advanced*	Presentation communicates the topic in clear and compelling manner. Presentation exhibits an adequate grasp of content and method of production.
3	*Proficient*	Presentation communicates topic in clear and compelling manner. The content and/or the method of production needs more work.
2	*Developing*	Presentation shows work and effort but is vague or missing key elements necessary to communicate the topic.
1	*Novice*	Presentation shows little effort and/or poorly communicates the topic.
0	*No Evidence*	Presentation does not communicate the topic.

* Note: Adapted from SmartLab Project Self-Assessment Rubric.

Student checklist:

• My presentation communicates the topic in a clear way.	
• My presentation is interesting and convincing.	
• My presentation showcases my expertise in using the software, hardware, or materials that my group used to make our solution.	