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An Evaluation of STEM Integration Effectiveness by Artifact Analysis

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Abstract

Improving the learning experience is the purpose of integrating curricula and providing students with explicit connections between disciplines. However, the mainstream application of STEM Integration often forsakes academic areas which are not within the scope of Science, Technology, Engineering, and Mathematics. If STEM Integration continues as a practice and method of instruction, care should be taken as to how it is applied. This paper utilizes a modified version of the Engineering Design Process Portfolio Scoring Rubric (EDPPSR) as a method of evaluating technology students' design portfolio in a design thinking course. Through artifact analysis using the EDPPSR, students' self-documented design processes are evaluated on twelve different elements. The purpose of this paper is to pilot the research methods of using the EDPPSR and multiple raters.

Introduction

STEM education manifests in many ways but this wave of STEM Thinking has made an impact in the form of STEM Integration. "STEM Thinking can lead teachers to become STEM integrators who can teach students how to apply STEM subject matter in a variety of "real-world" inquiry-based learning activities" (Reeve, 2015). Wang, Moore, Roehrig & Park (2011) explain it differently, "STEM integration is a curricular approach that combines the concepts of STEM in an interdisciplinary teaching approach." The impact of this STEM Integration movement is somewhat controversial because there is no clear definition of the method. However, STEM educators agree that the goal of integration is to increase STEM literacy, develop 21st century competencies, perpetuate STEM workforce readiness, generate student interest and engagement, and teach students to make connections among STEM disciplines (Honey, Pearson, & Schweingruber, 2014). Explicit connections are commonly being made in the context of engineering and technology, which are known for design activities. "These technological and engineering contexts bring attention to the increasingly important role that STEM plays in our society and emphasize how STEM affects our everyday existence" (De La Paz, 2013).

At a state-sponsored university, in a college of technology, educators are working towards a STEM Integration model for their first-year gateway course, Design Thinking in Technology. Design Thinking in Technology is a required, college-specific course for a Bachelor of Science degree. In this course, students are expected critically think about the user's contexts, narrow in on a design problem within context of the global grand challenges, and the implications of previous solutions. Students are also expected to synthesize multiple data source to make informed design judgements. To provide evidence for their design process, students must be able to communicate in both a oral and written format. During the fall semester of 2016, there were six integrated sections and six non-integrated sections of this Design Thinking course. In the integrated versions of this course, explicit connections are made to required undergraduate courses in Communication and English, the students' required humanities courses (Chesley, Mentzer, Jackson, Laux, Renner, 2016). Instructors from each subject, Technology, Communications, and English, collaborate and weave the curricula together to form those explicit connections. An example of this collaboration is a final project that is developed across all three disciplines and presented as a culmination of their work in all three courses.

The purpose of this paper is to explore research methods and assess the validity of using the Engineering Design Process Portfolio Scoring Rubric (EDPPSR) to analyze students' final design journals in both integrated and non-integrated sections. This Rubric is intended to measure students' abilities to document their design processes. For this paper, multiple researchers evaluated artifacts using the EDPPSR evaluation rubric. This pilot study will enable researchers to further assess and analyze the impact of STEM-humanities integration on students' design process abilities.

Background and Related Work

Design is inherently a difficult subject to teach due to the unique epistemology required to become an expert. Several design theories describe an epistemology which requires that knowledge be constructed by experience. This is different from traditional epistemologies found in academic institutions, where traditionally knowledge is gathered and passed on from expert to novice. In design education, an expert is a practitioner who has special knowledge which was acquired through practice and it is impossible to impart the unique knowledge derived from those experiences. Authors Dreyfus and Dreyfus (2005) explained it best:

> *If one asks an expert for the rules he or she is using, one will, in effect, force the expert to regress to the level of a beginner and state the rules learned in school. Thus, instead of using rules he or she no longer remembers, as the knowledge engineers suppose, the expert is forced to remember rules he or she no longer uses... No amount of rules and facts can capture the knowledge an expert has when he or she has stored experience of the actual outcomes of tens of thousands of situations.*

Knowledge that is learned through experience and constructed through continual practice can also be described as a tacit-knowledge or *knowing-in-action* (Schön, 1995). "I submit that such knowing-in-action makes up the great bulk of what we know how to do in everyday and in professional life. It is what gets us through the day" (Schön, 1995). In his paper describing this knowing-in-action, Schön suggests a concept like Dreyfus and Dreyfus, an expert who tries to teach their craft or practice must reflect on specific situations and contexts to describe how they would approach them. It is in this manner that design knowledge is created, reflecting on the practice and process to develop a knowledge base unique to each designer. Schön describes this event as either reflection-in-action or reflection-on-action.

This reflection practice is crucial to design, for building knowledge and for developing a best practice. Reflection is also common in the relationship between a problem and solution; well designed solutions align with the problem stated at the beginning of the process. It is the iterative process of reflecting and aligning problem and solution that gives credence to the concept of Problem and Solution co-evolution (Rittel & Webber, 1984). "To find the problem is thus the same thing as finding the solution; the problem cannot be defined until the solution has been found" (Rittel & Webber, 1984). Essentially, when working with a complex design problem, also called a wicked problem, the designer is looking to define the problem in a specific context. "One cannot understand the problem without knowing about its context; one cannot meaningfully search for information without the orientation of a solution concept; one cannot first understand, then solve" (Rittel & Webber, 1984). The process of defining the problem, researching, reflecting, ideating, and reflecting building an understanding of the context in which the problem is situated. After fully understanding the solution and the problem, a designer reflects on the process and alignment to build their knowledge base so that they can apply the principles learned from their experience to a new problem and context.

Designers therefore have the capacity to reflect-in-action and reflect-on-action, define the problem and solution simultaneously, and organize their thoughts before acting. It is incumbent on practitioners to know how to organize their thoughts and communicate them effectively. Why did they decide on this solution? Why did they brainstorm these alternatives? How did they arrive at this problem and context? Who are they communicating with and why? Designers must provide logical rationale for their decisions and evaluate themselves on the performance. In this manner they develop their own Design Thinking mindset.

Engineering Design Process Portfolio Scoring Rubric

The Engineering Design Process Portfolio Scoring Rubric (EDPPSR) originated from a project in 2004-2005 as a way of evaluating engineering design education in K-12 (Groves, Abts, Goldberg, 2014). The purpose of the EDPPSR was to "allow student performance in the underlying knowledge and skill areas to be reliably and repeatably[*sic*] rated" (Groves, Abts, Goldberg, 2014, p.24.1321.4). The initial pilot of the rubric was run in 2010 and was later revised in 2011. The rubric houses 14 elements of the engineering design process, all identified by a team through their collective engineering design experience and expertise in performance-based assessment. Each element within the EDPPSR is evaluated at one of six scoring levels: 0 (no evidence), 1 (novice), 2 (developing), 3 (proficient), 4 (advanced), and 5 (exemplary) all scoring levels are further described at length for more consistent evaluation(See Appendix A). The process of validating this rubric for engineering design education purposes was ongoing as of 2014 (Groves, Abts, Goldberg, 2014). Through the use of workshops funded by the National Science Foundation (NSF), each element of the rubric is being evaluated for its reliability and validity. Although the rubric is still being refined, we selected the rubric for this study because the elements aligned with the project outcomes of the assignment artifacts we collected. The elements being evaluated in the design process of the Design Thinking course were in parallel with those the EDPPSR was created to measure. This study looks to see if those assumptions are accurate in evaluating the EDPPSR as a means for assessing students' design journals for their final design project.

Method

It is for the purpose of better developing a Design Thinking mindset in first-year college students that the Design Thinking course has integrated their curriculum with that of the Communications and English departments. Making explicit connections, thinking critically about problems and solutions, and communicating effectively are common objectives among these three disciplines. To explore whether this integration is improving student learning, final design journals from students in both integrated sections and non-integrated sections of the course were compared. The design journals were used as the best assessment method because they are "worthwhile activities that relate to (our) instructional outcomes and allow (our) students to demonstrate what they know and can do" (Perlman, 2003, p.3).

The final project in the Design Thinking course is based on a global challenge chosen by each team of students. Students are required to localize a problem related to the challenge and develop a solution, which they eventually prototype and test. Throughout the project, students are asked to communicate their process and results. Students are encouraged to be human-centered in their efforts and collaborative in their decisions and actions—tasks that require critical thought and the ability to understand other people. These global grand challenges, from which the problems for this project were derived could be considered *wicked problems* (Rittel & Webber, 1984) and these challenges generally impact society differently depending on the context in which they are addressed. Wicked problems are described as such due their tricky characteristics; this tricky nature comes from the human factor in all issues regarding society. Defining the problem can be viewed as setting boundaries for the design and creating a context for possible solutions. This is known as the co-evolution of problem and solution, "to find the problem is thus the same thing as finding the solution; the problem cannot be defined until the solution has been found" (Rittel & Webber, 1984). These types of problems also have no stopping rule, "the process of solving the problem is identical with the process of understanding its nature, because there are no criteria for sufficient understanding, and because there are no ends to the causal chains that link interacting open systems, the would-be planner can always try to do better" (Rittel & Webber, 1984). The ideal solutions for these problems are impossible to achieve; therefore a designer must approximate the problem and solution while also considering possible alterations through reflection. Wicked problems by their nature are iterative, progressive iterations of the problem should follow a logical path, decisions made during the design process should be explicit and explained. Students' documentation of this process will be the basis of our artifact analysis. The journey from problem to solution is the emphasis of their design journal deliverable, a primary form of communication for their design process. This study looks at the design journal as a unit of analysis because it is the culmination of the students' processes.

The final design journal assignment required a full documentation of the final project described above. Analyzing the design journals from this capstone project should provide an indication of the students' design thinking mindset after the course instruction. A sample of 92 artifacts was collected from students enrolled in the Design Thinking course during the same Fall 2016 semester. The sample size of 92 was chosen to demonstrate the research method and validate its effectiveness. Sampling of the artifacts yielded a data set with 44 design journals from the integrated sections and 48 from the non-integrated sections. All artifacts were sampled from the final design project and evaluated with the Engineering Design Process Portfolio Scoring Rubric (see Appendix A). This rubric was chosen because it aligned with the stated purpose of the final project and it quantifies evidence of the students' Design Thinking mindset.

To minimize researcher bias, our evaluation of the design journals was completed as a blind research study, and all design journals were deidentified prior to evaluation. The final design journals utilized in this study are assigned as the culmination of the students' final semester project. The final design journal was an overarching portfolio describing the design process of each team. Each required element of the design journal was laid out for students in a journal template, so students would be aware of the necessary steps and components of the final journal submission. The journal was an ongoing assignment throughout the final project rather than an additional submission of the project. The worthwhile nature of the project and the clearly defined outcomes were essential for the use of this assessment document (Perlman, 2003). A project is worthwhile if it contributes to the overall outcomes of the course, meaning it is not out of place in the context of the learning outcomes.

Analysis

Our research team received all Fall 2016 design journals from the individual instructors of each section of the course after the semester concluded. Grades for each assignment were not attached, ensuring there would be no unnecessary bias in researchers' evaluations. All data identifying individuals and instructors was removed. We collected 92 design journals with student permission for evaluation. For this pilot study, the research team randomly selected 20 design journals, equally distributed between integrated and non-integrated sections, to be evaluated utilizing the EDPPSR. Given that the current research is a pilot study, all 20 design journals were evaluated by both researchers. Treece and Treece (1982) suggest pilot studies should look at 10% of the overall project sample size. At a minimum this study would need to have evaluated 10 journals (Hill, 1998; Isaac & Michael, 1995). This study looks at approximately 22% of the overall sample size of the parent project.

It was the goal of the researchers to evaluate final design journals utilizing the EDPPSR, previously not used for grading, in an effort to better understand the students' abilities to communicate their design process. Through the initial evaluation of the journals, two elements in the rubric were deemed irrelevant for this particular artifact. Element E, the application of STEM principles and practices, was omitted from the evaluation because students had not been asked to evaluate their own designs utilizing these principles. There was no evidence in the final design journals that this element was a part of the curriculum and was thus removed. Element M, presentation of the project portfolio, was likewise omitted. While there was an in class final presentation for the project, researchers were not evaluating the oral presentations but rather the written documentation. All other elements of the rubric were evaluated on a 0-5 scale as prescribed in the original rubric. In this rubric, 5 is the high rank and 0 means there is no evidence of the element. For example, on Element A, a design journal received evaluation of 5 if "The problem is clearly and objectively identified and defined with considerable depth, and it is well elaborated with specific detail; the justification of the problem highlights the concerns of many primary stakeholders and is based on comprehensive, timely, and consistently credible sources; it offers consistently objective detail from which multiple measurable design requirements can be determined." Each design journal was evaluated and each element scored independently by both researchers.

Interrater Reliability

The researchers evaluated approximately 22% of the journals and analyzed their level of agreement on each element. All initial variation of researcher scores was minimized through discussion and compromise about the meaning and intent of the rubric.

In order to conduct further research on the data in relation to course integration, the researchers needed to identify if the EDPPSR was a reliable rubric for journal evaluation. The reliability of the EDPPSR as a tool to mean to measure the design journals in this study was evaluated by utilizing Cronbach's alpha. Cronbach's alpha is the measure of agreement between two or more raters on a multi-point scale, the closer the value is to one the more reliable the scale is, in this case the EDPPRS. Due to the nature of the EDPPRS, a 0-5 scale for each element of the design portfolio, Cronbach's alpha was the appropriate interrater reliability test to run. Cronbach's alpha was employed for the sole purpose of determining the average correlation of each element in the rubric to gauge its reliability (Cronbach, 1951). The interrater reliability data is presented for each evaluated element of the rubric in Table 1, along with the average interrater reliability across all elements.

Table 1. Cronbach's alpha for Engineering Design Process Portfolio Scoring Rubric

Engineering Design Process Portfolio Scoring Rubric	Cronbach's alpha
Element A: Presentation and justification of the problem	0.75
Element B: Documentation and analysis of prior solution attempts	0.76
Element C: Presentation and justification of solution design requirements	0.95
Element D: Design concept generation, analysis, and selection	0.89
Element F: Consideration of design viability	0.94
Element G: Construction of testable prototype	0.96
Element H: Prototype testing and data collection plan	0.96
Element I: Testing, data collection and analysis	0.95
Element J: Documentation of external evaluation	0.96
Element K: Reflection on the design project	0.93
Element L: Presentation of designer's recommendations	0.95
Element N: Writing like an Engineer	0.75
Average interrater reliability	0.90

Discussion

Application of the evaluation instrument to the artifacts demonstrated the validity of utilizing the Engineering Design Process Portfolio Scoring Rubric on design journals in a technology course. Using interrater reliability and the EDPPSR rubric will make future artifact analysis with this tool a valid research method. This reliability is demonstrated by the Cronbach's alpha values achieved by the researchers; a value of 0.7 is an acceptable reliability coefficient (Nunnaly, 1978).

Similar to the wicked problems presented to the students in their projects, finding agreement for the interrater reliability is difficult due to the human element. For future research into the effectiveness of STEM integration in the Design Thinking in Technology course, a larger sample of artifacts will be analyzed and the artifacts will be selected to minimize outside biases which could skew the data. Since the interrater reliability and EDPPSR are valid methods of analysis, the next step is apply this method to a sample of design journals which accurately represents the wider student populations. This next step will allow the researchers to evaluate the effectiveness, in developing a Design Thinking mindset, of the STEM-humanities integration model.

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Appendix A: Engineering Design Process Portfolio Scoring Rubric

Element A: Presentation and justification of the problem

5 The problem is clearly and objectively identified and defined with considerable depth, and it is well elaborated with specific detail; the justification of the problem highlights the concerns of many primary stakeholders and is based on comprehensive, timely, and consistently credible sources; it offers consistently objective detail from which multiple measurable design requirements can be determined.

4 The problem is clearly and objectively identified and defined with some depth, and it is generally elaborated with specific detail; the justification of the problem highlights the concerns of some primary stakeholders and is based on various timely and generally credible sources; it offers generally objective detail from which multiple measurable design requirements can be determined.

3 The problem is somewhat clearly and objectively identified and defined with adequate depth, and it is sometimes elaborated with specific detail, although some information intended as elaboration may be imprecise or general; the justification of the problem highlights the concerns of at least a few primary stakeholders and is based on at least a few sources which are timely and credible; although not all information included may be objective, the justification of the problem offers enough objective detail to allow at least a few measurable design requirements to be determined.

2 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; the justification of the problem highlights the concerns of only one or two primary stakeholders and/or may be based on insufficient sources or ones that are outdated or of dubious credibility; although little information included is objective, the justification of the problem offers enough objective detail to allow at least a few design requirements to be determined; however, these may not be ones that are measurable.

1 The identification and/or definition of the problem is unclear, is unelaborated, and/or is clearly subjective; any intended justification of the problem does not highlight the concerns of any primary stakeholders and/or is based on sources that are overly general, outdated, and/or of dubious credibility; information included is insufficient to allow for the determination any measurable design requirements.

0 The identification and/or definition of the problem are missing OR cannot be inferred from information included. A justification of the problem is missing, cannot be inferred from information included as evidence, OR is essentially only the opinion of the researcher.

Element B: Documentation and analysis of prior solution attempts

5 Documentation of plausible prior attempts to solve the problem and/or related problems is drawn from a wide array of clearly identified and consistently credible sources; the analysis of past and current attempts to solve the problem—including both strengths and shortcomings— is consistently clear, detailed, and supported by relevant data.

4 Documentation of existing attempts to solve the problem and/or related problems is drawn from a variety of clearly identified and consistently credible sources; the analysis of past and current attempts to solve the problem—including both strengths and shortcomings—is clear and is generally detailed and supported by relevant data.

3 Documentation of existing attempts to solve the problem and/or related problems is drawn from several—but not necessarily varied—clearly identified and generally credible sources; the analysis of past and current attempts to solve the problem—including both strengths and shortcomings—is generally clear and contains some detail and relevant supporting data.

2 Documentation of existing attempts to solve the problem and/or related problems is drawn from a limited number of sources, some of which may not be clearly identified and/or credible; the analysis of past and current attempts to solve the problem—including strengths and/or shortcomings—is overly general and contains little detail and/or relevant supporting data.

1 Documentation of existing attempts to solve the problem and/or related problems is drawn from only one or two sources that may not be clearly identified and/or credible; the analysis of past and current attempts to solve the problem—including strengths and/or shortcomings—is vague and is missing any relevant details and/or relevant supporting data.

0 Documentation of existing attempts to solve the problem and/or related problems is missing or minimal (a single source that is not clearly identified and/or credible) OR cannot be inferred from information intended as analysis of past and/or current attempts to solve the problem.

Element C: Presentation and justification of solution design requirements

5 Design requirements are listed and prioritized, and they are consistently clear and detailed; these design requirements presented are consistently 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, and have been validated by, many if not all primary stakeholder groups.

4 Design requirements are listed and prioritized, and they are generally clear and detailed; these design requirements presented are 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, and have been validated by, several primary stakeholder groups.

3 Design requirements are listed and prioritized, and they are generally clear and somewhat detailed; these design requirements presented are 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, and have been validated by, at least a few primary stakeholder groups.

2 Design requirements are listed and prioritized, but some/all of these 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/and or have been validated by, only one primary stakeholder group.

1 An attempt is made to list, format, and prioritize requirements, but these 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 have been validated by, any primary stakeholder groups.

0 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.

Element D: Design concept generation, analysis, and selection

5 The process for generating and comparing possible design solutions was comprehensive, iterative, and consistently defensible, making a viable and well-justified design highly likely; the design solution ultimately chosen was well-justified and demonstrated attention to all design requirements; the plan of action has considerable merit and would easily support repetition and testing for effectiveness by others.

4 The process for generating and comparing possible design solutions was thorough, iterative, and generally defensible, making a viable design likely; the design solution chosen was justified and demonstrated attention to most if not all design requirements; the plan of action would support repetition and testing for effectiveness by others.

3 The process for generating and comparing possible design solutions was adequate and generally iterative and defensible, making a viable design possible; the choice of design solution was explained with reference to at least some design requirements; the plan of action might not clearly or fully support repetition and testing for effectiveness by others.

2 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; there is insufficient detail to allow for testing for replication of results.

1 The process for generating a possible design solution was incomplete and was only minimally iterative and/or defensible; any attempted explanation for the design solution chosen lacked support related to design requirements and cannot be tested.

0 There is no evidence an attempt to arrive at a design solution through an iterative process based on design requirements.

Element F: Consideration of design viability

5 The proposed design was carefully reviewed based on several relevant extra-functional considerations; a judgment about design viability based on those considerations—the capacity of the proposed solution to address the problem—is clearly realistic and well supported with credible evidence.

4 The proposed design was adequately reviewed based on several relevant extra-functional considerations; a judgment about design viability based on those considerations—the capacity of the proposed solution to address the problem—is generally realistic and adequately supported with credible evidence.

3 The proposed design was partially reviewed based on one or two relevant extra-functional considerations; a judgment about design viability based on those considerations—the capacity of the proposed solution to address the problem—is only somewhat/sometimes realistic and is only partially supported with credible evidence.

2 The proposed design was superficially reviewed based on one or two relevant extra-functional considerations; a judgment about design viability based on those considerations—the capacity of the proposed solution to address the problem—may be generally although not completely unrealistic and/or may be inadequately supported with credible evidence.

1 The proposed design was superficially reviewed based on one or two extra-functional considerations of marginal relevance; a judgment about design viability based on those considerations—the capacity of the proposed solution to address the problem—may be unrealistic and/or not supported with any credible evidence.

0 There is no evidence provided that the proposed design was reviewed based on any extrafunctional considerations.

Element G: Construction of a testable prototype

5 The final prototype iteration is clearly and fully explained and is constructed with enough detail to assure that objective data on all or nearly all design requirements could be determined; all attributes (sub-systems) of the unique solution that can be tested or modeled mathematically are addressed and a well-supported justification is provided for those that cannot be tested or modeled mathematically and thus require expert review.

4 The final prototype iteration is clearly and adequately explained and is constructed with enough detail to assure that objective data on many design requirements could be determined; most attributes (sub-systems) of the unique solution that can be tested or modeled mathematically are addressed and a generally supported justification is provided for those that cannot be tested or modeled mathematically and thus require expert review.

3 The final prototype iteration is clearly and adequately explained and is constructed with enough detail to assure that objective data on some design requirements could be determined; some attributes (sub-systems) of the unique solution that can be tested or modeled mathematically are addressed and an adequately supported justification is provided for those that cannot be tested or modeled mathematically and thus require expert review.

2 The final prototype iteration is explained only somewhat clearly and/or completely and is constructed with enough detail to assure that objective data on at least a few design requirements could be determined; a few attributes (sub-systems) of the unique solution that can be tested or modeled mathematically are addressed but there may be insufficient justification for those that cannot be tested or modeled mathematically and thus require expert review.

1 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 requirements could be determined; no more than one attribute (sub-system) of the unique solution that can be tested or modeled mathematically is addressed and any attempt at justification for those that cannot be tested or modeled mathematically and thus require expert review is missing.

0 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.

Element H: Prototype testing and data collection plan

5 The testing plan addresses all or nearly all of the high priority design requirements by effectively describing the conduct (through physical and/or mathematical modeling) of those tests that are feasible based on the instructional context and providing for others a logical and well-developed explanation confirmed by one or more field experts of how testing would yield objective data regarding the effectiveness of the design.

4 The testing plan addresses many of the high priority design requirements by describing in a generally effective way the conduct (through physical and/or mathematical modeling) of those tests that are feasible based on the instructional context and providing for others a logical and generally developed explanation confirmed by one or more field experts of how testing would yield objective data regarding the effectiveness of the design.

3 The testing plan addresses some of the high priority design requirements by adequately describing the conduct (through physical and/or mathematical modeling) of those tests that are feasible based on the instructional context and providing for others a generally logical and adequately developed explanation confirmed by one or more field experts of how testing would yield objective data regarding the effectiveness of the design.

2 The testing plan addresses a few of the high priority design requirements by at least partially describing the conduct (through physical and/or mathematical modeling) of those tests that are feasible based on the instructional context and providing for others an only somewhat logical and/or partially developed explanation confirmed by one or more field experts of how testing would yield objective data regarding the effectiveness of the design.

1 The testing plan addresses one of the high priority design requirements by describing at least minimally the conduct (through physical and/or mathematical modeling) of a test that is feasible based on the instructional context and/or providing for an at least generally logical and/or partially developed explanation of how testing would yield objective data regarding the effectiveness of the design; confirmation of that explanation by even one field expert may be missing.

0 Any testing plan included fails to address at least one of the high priority design requirements by describing at least minimally the conduct (through physical and/or mathematical modeling) of a test that is feasible based on the instructional context and/or providing for an at least generally logical and/or partially developed explanation of how testing would yield objective data regarding the effectiveness of the design; OR a testing plan is missing altogether.

Element I: Testing, data collection and analysis

5 Through the conduct of several tests for high priority requirements that are reasonable based on instructional contexts, or through physical or mathematical modeling, the student demonstrates considerable understanding of testing procedure, including the gathering and analysis of resultant data; the analysis of the effectiveness with which the design met stated goals includes a consistently detailed explanation [and summary] of the data from each portion of the testing procedure and from expert reviews, generously supported by pictures, graphs, charts and other visuals; the analysis includes an overall summary of the implications of all data for proceeding with the design and solving the problem.

4 Through the conduct of several tests for high priority requirements that are reasonable based on instructional contexts, or through physical or mathematical modeling, the student demonstrates ample understanding of testing procedure, including the gathering and analysis of resultant data; the analysis of the effectiveness with which the design met stated goals includes a generally detailed explanation [and summary] of the data from each portion of the testing procedure and from expert reviews, generally supported by pictures, graphs, charts and other visuals; the analysis includes an overall summary of the implications of most if not all of the data for proceeding with the design and solving the problem.

3 Through the conduct of a few tests for high priority requirements that are reasonable based on instructional contexts, or through physical or mathematical modeling, the student demonstrates adequate understanding of testing procedure, including the gathering and analysis of resultant data; the analysis of the effectiveness with which the design met stated goals includes a somewhat detailed explanation [and summary] of the data from each portion of the testing procedure and from expert reviews, at least somewhat supported by pictures, graphs, charts and other visuals; the analysis includes a summary of the implications of at least some of the data for proceeding with the design and solving the problem.

2 Through the conduct of one or two tests for high priority requirements that are reasonable based on instructional contexts, or through physical or mathematical modeling, the student demonstrates partial or overly general understanding of testing procedure, including the gathering and analysis of resultant data; the analysis of the effectiveness with which the design met stated goals includes a partial explanation [and summary] of the data (partially complete and/or partially correct), at least minimally supported by pictures, graphs, charts and other visuals; the analysis includes a partial and/or overly-general summary of the implications of at least some of the data for proceeding with the design and solving the problem.

1 Through the conduct of one or two tests for requirements (which may or may not be high priority) that are reasonable based on instructional contexts, or through physical or mathematical modeling, the student demonstrates minimal understanding of testing procedure, including the gathering and analysis of resultant data; the analysis of the effectiveness with which the design met stated goals includes an attempted explanation [and summary] of the data but may not be supported by any pictures, graphs, charts or other visuals; the analysis may be missing even a partial and/or overly-general summary of the implications of any of the data for proceeding with the design and solving the problem.

0 Any test(s) for requirement(s) or attempts at physical or mathematical modeling fail to demonstrate even minimal understanding of testing procedure, including the gathering and analysis of resultant data; OR there is no evidence of testing or physical or mathematical modeling to address any requirements.

Element J: Documentation of external evaluation

5 Documentation of project evaluation by multiple, demonstrably qualified stakeholders and field experts is presented and is synthesized in a consistently specific, detailed, and thorough way; documentation is sufficient in two or more categories to yield meaningful analysis of that evaluation data; the synthesis of evaluations consistently addresses evaluators' specific questions, concerns, and opinions related to design requirements.

4 Documentation of project evaluation by two or more demonstrably qualified stakeholders and field experts is presented and is synthesized in a generally specific, detailed, and thorough way; documentation is sufficient in at least one category to yield a meaningful analysis of that evaluation data; the synthesis of evaluations generally addresses evaluators' specific questions, concerns, and opinions related to design requirements.

3 Documentation of project evaluation by three or four demonstrably qualified stakeholders and/or field experts is presented and is synthesized in a somewhat specific and detailed way, but may not be thorough; documentation may not be sufficient in any category to yield a meaningful analysis of that evaluation data; the synthesis of evaluations addresses at least some of evaluators' specific questions, concerns, and opinions related to design requirements.

2 Documentation of project evaluation by two or three representatives of stakeholders and/or field experts (some of whom may not be demonstrably qualified) is presented and is synthesized in a somewhat specific and/or detailed but incomplete or overly general way; the synthesis of evaluations addresses at least a few of evaluators' specific questions, concerns, and/or opinions related to design requirements.

1 Documentation of project evaluation by one or two representatives of stakeholders and/or field experts is presented but synthesis is sparse, with few specifics/details; the synthesis of evaluations addresses only one or two of an evaluator's questions, concerns, and/or opinions related to design requirements.

0 Documentation of project evaluation by any representative stakeholder or field expert is nonexistent OR if included is minimal; synthesis is minimal or missing and if present, does not address any questions, concerns, or opinions of an evaluator related to design requirements.

Element K: Reflection on the design project

5 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 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 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 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 includes some lessons learned which would be useful to others attempting the same or similar project.

1 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 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.

Element L: Presentation of designer's recommendations

5 The project designer includes consistently detailed and salient recommendations regarding the conduct of the same or similar project in the future; recommendations include caveats as warranted and specific ways the project could be improved with consistently detailed plans for the implementation of those improvements

4 The project designer includes generally detailed and salient recommendations regarding the conduct of the same or similar project in the future; recommendations include caveats as warranted and specific ways the project could be improved with generally detailed plans for the implementation of those improvements

3 The project designer includes a few detailed and salient recommendations regarding the conduct of the same or similar project in the future; recommendations include some specific ways the project could be improved along with what may be only minimally detailed plans for the implementation of those improvements and may also include one or two caveats for others

2 The project designer includes recommendations regarding the conduct of the same or similar project in the future; recommendations may include some specific ways the project could be improved but plans for the implementation of those improvements may be missing OR the recommendations (with or without plans) may be partial and/or overly general.

1 The project designer includes one or two overly general and/or questionably relevant recommendations regarding the conduct of the same or similar project in the future; any plans for implementation included are vague/unclear or minimally related to the recommendations provided.

0 The project designer includes one or two recommendations (with or without plans) that bear little/no relation to the conduct of the same or similar project in the future OR fails to offer any recommendations or plans regarding the conduct of the same or similar project in the future.

Element N: Writing like an Engineer

5 Abundant evidence of the ability to write consistently clear and well organized texts that are developed to the fullest degree suitable for the audience and purposes intended (to explain, question, persuade, etc.); texts consistently demonstrate the ability to adjust language, style and tone to address the needs and interests of a variety of audiences (e.g., expert, informed, general/lay audience) and to use a wide variety of forms which are commonplace among STEM disciplines (e.g., notes, descriptive/narrative accounts, research reports); where required by convention, appropriate documentation in standardized form (e.g., APA) is consistently evident.

4 Evidence of the ability to write clear and well organized texts that are generally well-developed for the audience and purposes intended (to explain, question, persuade, etc.); texts generally demonstrate the ability to adjust language, style and tone to address the needs and interests of a variety of audiences (e.g., expert, informed, general/lay audience) with minor exceptions and demonstrate the ability to use a variety of forms which are commonplace among STEM disciplines (e.g., notes, descriptive/narrative accounts, research reports); where required by convention, appropriate documentation in standardized form (e.g., APA) is generally evident.

3 Adequate evidence of the ability to write usually clear and generally organized texts that are at least partially developed for the audience and purposes intended (to explain, question, persuade, etc.); texts demonstrate the ability to adjust language, style and tone to address the needs and interests of several different audiences (e.g., expert, informed, general/lay audience) but may be unsuccessful at doing so on occasion; texts demonstrate the ability to use a several different forms which are commonplace among STEM disciplines; where required by convention, appropriate documentation in standardized form (e.g., APA) is sometimes evident, although attempts at documentation may reveal minor errors

2 Only some evidence of the ability to write clear and organized texts that are at least partially developed for the audience and purposes intended (to explain, question, persuade, etc.); texts demonstrate some ability to adjust language, style and tone to address the needs and interests of at least two different audiences (e.g., expert, informed, general/lay audience) but adjustments are not evident—although warranted—in a number of instances; texts demonstrate the ability to use at least two different forms which are commonplace among STEM disciplines; where required by convention, appropriate documentation in standardized form (e.g., APA) is frequently missing or incorrect.

1 Little evidence of the ability to write clear and organized texts that are at least partially developed for the audience and purposes intended (to explain, question, persuade, etc.); texts demonstrate little ability to adjust language, style and tone to address the needs and interests of at least two different audiences (e.g., expert, informed, general/lay audience) but many adjustments are not evident— although warranted; texts demonstrate the attempt to use at least two different forms which are commonplace among STEM disciplines; appropriate documentation in standardized form (e.g., APA) is usually missing or incorrect.

0 Virtually no evidence of the ability to write even somewhat clear and organized texts that are developed for the audience and purposes intended (to explain, question, persuade, etc.); texts demonstrate virtually no ability to adjust language, style and tone to address the needs and interests of at least two different audiences (e.g., expert, informed, general/lay audience); there may be evidence of an attempt to use at least two different forms which are commonplace among STEM disciplines but these are not correctly differentiated; there is virtually no evidence of any attempt to provide documentation in standardized form where needed.