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A Pathway to Create and Validate an Engineering Design Rubric across All Engineering Programs

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1. Introduction

Engineering curricula have traditionally been developed around fundamental engineering courses and this has resulted in programs prioritizing simple problem-solving activities over open-ended problem-solving and integrative design learning experiences [1], [2], [3]. Although many engineering schools have cornerstone and capstone projects that contain significant design opportunities for students in the first year and senior year, respectively [4], there is a need to scaffold student's design skills throughout an entire curriculum [5].

A critical need in curriculum development is the ability to assess student design knowledge. In the engineering education literature, there have been numerous studies that reformulated engineering programs or developed design activities from different perspectives [3], [6], [7], [8], [9]. Different types of student's design assessments have been used by instructors including self, peer, and expert assessments of design reports, final product performances, open- and close-ended questions, videos of design teams, and students' portfolios [10]. Measuring student design knowledge has several complexities and each assessment has its advantages and disadvantages.

By conducting a systematized literature review and summarizing some significant research studies in this area, which are described in the next sections, we found that there is a need for a comprehensive rubric and approach to measure students' design skills longitudinally and throughout an entire curriculum, based on the ABET design definition and Bloom's Taxonomy.

1.1. Scope and research questions

This is a work-in-progress paper which is part of an ongoing research project, including four stages:

1) Reviewing design assessment tools in engineering education (traditional (narrative) literature review) and conducting a systematized literature review about design knowledge assessment methods.
2) Developing a rubric and a systematic approach to measure engineering student design knowledge longitudinally.
3) Collecting data in some engineering classrooms to validate the rubric.
4) Collecting data across programs in the College of Engineering over all four years and conducting longitudinal design knowledge assessment.

This work-in-progress paper includes the first two stages of this research project. In the first step, our systematized literature review is focused on the papers that are related to design knowledge assessment methods in any disciplines, and our traditional literature review covers additional studies in engineering education. For this part, the research question is:

Research question: *What design knowledge assessment tools, longitudinally or cross-sectional; program level or college level, have been investigated by different design scholars?*

Then, the goal of the second step is to propose a general rubric that could be adopted, customized based on design projects, and used by engineering instructors. Data collection for the third step, to validate the rubric, is ongoing.

2. Traditional literature review

There are some well-known and well-cited engineering education literature that has provided guideline to assist instructors in teaching students design skills and suggested different pedagogies to improve student skills in different design phases [11], [12]. For design skill assessment, in engineering education, another research study created and validated a rubric for first-year engineering student self-assessment based on the quality function development framework (the framework that emphasizes the customer need) [13]. A different study developed a rubric to evaluate first-year and senior student design knowledge based on different levels of Bloom's taxonomy using pre- and post-tests. Students were asked to critique the design processes and the proposed strategies. Then evaluators, using a rubric, graded them based on the quality of their answers [13]. Also, an additional study provided an innovation-focused design outcomes measurement for a senior design course based on the experts' comments [14].

3. Systematized literature review

While a traditional literature review summarizes related studies without any method, a systematized literature review includes a methodological approach. In this section, a systematized literature review has been conducted to complement our literature review and cover more design assessment tools.

3.1. Method

For this step, we selected a systematized literature review over other literature review methods, such as scoping literature or rapid review, because a systematized literature review uses a specified methodology to answer a specific research question [15], [16].

3.2. Search indexes

Scopus and ASEE databases were selected for this study. Scopus encompasses many peer-reviewed journal articles in engineering and ASEE is the premier Engineering Education society and a good resource for ideas and projects in engineering education that might not be fully developed into journal papers.

3.3. Keywords and search procedure

After evaluating different keywords in various combinations, our search strings were selected. We decided to make our search as broad as possible to find any related papers. Table 1 in the Appendix summarizes the final research strings with the date of the search and the number of articles identified.

3.4. Inclusion and exclusion criteria

Since we searched the ASEE as a source for engineering education conference papers, in the Scopus, we limited our search to peer review journal articles. Also, the search has been limited to the papers written and published in English in the United States, United Kingdoms, Australia, and Germany between 2000 and 2024. Finally, we excluded any studies in K12 or graduate level settings or studies that has not proposed a unique design knowledge assessment method. We specifically included only papers that have developed an assessment tool that measured student design knowledge and skills.

3.5. Selection process

By adopting the PRISMA flowchart [17], after using the mentioned research strings and removing duplicates, 298 papers have been reviewed at the title and abstract level. This review resulted in 255 articles that did not meet our criteria for inclusion. After reading the full papers, only 7 papers were selected for this systematized literature review.

3.6. Systematized literature review results

Our search did not result in any college-level assessment tool that assessed design skills across all engineering programs. So, results were divided into two sections: longitudinally at the program level and cross-sectional at the program level.

3.6.1. Longitudinally at program level

Crepeau et al [18], [19] conducted a research study in Mechanical Engineering at the University of Idaho that used a rubric to evaluate four student design competencies, including system design, implementation, project management, and documentation. Mechanical engineering faculty rated the final design projects and measured these competencies from pre-engineer to professional engineer levels. They conducted this study over five years from cornerstone to mid-programs and capstone projects. The rubric linked each competency with each ABET student outcome. For instance, they linked the project management to the fifth student outcome which is about student's ability to work in multidisciplinary teams. They found that success in the first-year design course is directly related to the success in the senior design course and students who participated in all cornerstones, mid-program, and capstone design courses had higher competencies compared to students who just took some of these courses.

Higbee and Miller [20] conducted a research study in the Biomedical Engineering (BME) that employed a pre and post-quiz method to measure student knowledge of design across the BME curriculum with an integrated design experience at the sophomore and junior level. Although this study has not introduced any specified rubric for assessing student design skills, they found that an integrated design experience and using an assessment tool improved student understanding of design, and the acquired skills in the lower level course assisted them in gaining more knowledge in the higher level courses.

3.6.2. Cross-sectional at program level

In a research paper in a Biological and Agricultural Engineering program, Douglas-Mankin [21] measured first-year student design knowledge, using self-evaluation, short answer exam, and presentation review. These assessments include seven design elements: teamwork, information gathering, problem definition, idea generation, evaluation and decision making, implementation, and communication. This evaluation assisted students in progressing toward the problem definition element. Although this study documented student design learning, the author did not use a rubric and used this assessment for just one semester and one class. Dasgupta et al. [22] performed a study in a Biological Science program that developed and validated a rubric for student experimental knowledge and challenges. In this rubric, based on their literature review, they have found challenging areas which include: "the variable properties of an experimental subject; the manipulated variables; measurement of outcomes; accounting for variability; and the scope of inference appropriate for experimental results." Although this rubric just specifies the areas of difficulty, it is a good resource for Biological Science instructors to navigate the student design knowledge when dealing with the common design challenges. Killpack and Fulmer [23] carried out another study in Biology and developed an interrelated experimental design tool to improve the instructor's rating reliability, to enhance student's design skills, and to evaluate components of experimental design.

Watson et al. [24] developed a rubric in a Civil Engineering senior design course to improve student's sustainable design skills. This rubric includes 14 criteria to evaluate student's performance in their capstone reports in four areas including environmental, social, design tool, and economic. In this study, students reflected on their design skills and rated their projects based on a rubric and discussed the results with other students. This formative rubric assessment assisted students in a better understanding of sustainable design.

4. Needs for a college level design assessment

Based on both literature review sections, the authors did not find any universal and comprehensive design knowledge assessment tool that can be used throughout an entire curriculum across all engineering programs at cornerstone, capstone, and middle-year design courses. In this study, we propose a rubric that:

- Accumulates and utilizes previous engineering design assessment tools.
- Would be used at the college level which proposes a common design language and general assessment criteria for engineering instructors. These criteria would be customized by instructors based on their learning objectives and design activities while trying to keep the structure consistent.
- Uses the ABET definition of design in the rubric elements and criteria.
- Links design activities and learning objectives with the revised Bloom's level of Taxonomy.
- Tracks student's progress longitudinally, based on the design knowledge in different design steps or the levels of Bloom's taxonomy, within and across years.
- Assists instructors in scaffolding student design knowledge by continuously giving students feedback about their design knowledge progress across each program.

5. Theoretical framework

For this study, the informed design teaching and learning matrix[1] [12] and constructivism learning theory[2] [25] have been used as our theoretical framework to give us a lens to frame all stages of our study. Based on the informed design teaching and learning matrix, instructors should develop pedagogical content and assessment to do informed teaching with each design task. These pedagogies and assessments assist students in developing their design skills from novice to informed. Additionally, based on constructivism learning theory, students should be able to build on their previous knowledge by reflecting on their previous knowledge and experiences and instructors should provide experiences that facilitate the construction of knowledge.

By considering this theoretical framework as a guideline, the goal of this on-going study is to propose an evaluation method that gives a tool to engineering instructors to provide informed design assessment while giving students a chance to receive formative feedback and construct their design knowledge based on design experiences.

6. Proposed Rubric

We decided to create a rubric for our assessment tool because rubrics are designed to be valid, reliable, efficient, fair, and effective evaluation tools that help instructors in student project assessment and help students to discover their strengths and weaknesses and learn about the process [26], [27]. For designing this rubric we considered several research paper guidelines in constructing a valid and reliable rubric, however, the validity of the rubric is going to be tested in the next phases of our study [28].

Also, design has a subjective nature and there is not a single right final design product for a design project, therefore, design knowledge assessment should be more focused on the process than the final product. However, evaluating the process is difficult as observing many students requires

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[1] A matrix that assist instructors and teachers to bring informed design activities into their classrooms and link their learning goals in design skills with teaching methods.

[2] Constructivism is 'an approach to learning that students can effectively build or create their own knowledge by their experiences while teacher facilitate the learning.

significant time and there is not a unique design process for design projects. Additionally, it is necessary to have a reliable design assessment at the individual level to assess student design knowledge in different design phases [29], [30], [31], [32]. So, this rubric should measure each student design knowledge during the design process in different design phases.

The proposed rubric can be found in Table 2 in the Appendix. We accumulated the findings from previous engineering design rubric studies to create this rubric. Based on literature review results, from rubrics in longitudinal studies and design matrix in our literature review, we found the importance of measuring student design skills from the pre-engineer levels to the professional levels [19] and realized the necessity of assessing the design skills acquired by integrated design activities across different years [20]. So, we decided to write our criteria with a common language that could be used across different years and disciplines, and based on the well-known engineering education literatures that specify novice and expert design behavior in engineering [11], [12]. These criteria help instructors to navigate student design knowledge from beginner to expert.
Design steps were merged into four categories (problem formulation, doing research and developing requirements, idea generation, prototyping, and evaluation), which is consistent with other engineering design assessment research [29]. Instructors or raters will rate student design reports in each related category from unacceptable to advanced. This approach also has been supported by previous studies [12], [18].

Additionally, we found that none of the previous engineering design assessment tools considered the ABET definition of design. Based on ABET: "*Engineering design is a process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. Engineering design involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs, for the purpose of obtaining a high-quality solution under the given circumstances. For illustrative purposes only, examples of possible constraints include accessibility, aesthetics, codes, constructability, cost, ergonomics, extensibility, functionality, interoperability, legal considerations, maintainability, manufacturability, marketability, policy, regulations, schedule, standards, sustainability, or usability.*" [33](p.7).

This rubric includes all design process steps and ABET design definitions as criteria for these categories. Also, Table 3 is designed to tie different course learning objectives with different design knowledge skills and the levels of the revised version of Bloom's taxonomy [34]. Different levels of Bloom's taxonomy would help instructors create their courses based on different levels of design knowledge and tie these levels to the design activities. Therefore, after each assessment, students have a grade for their level of design knowledge based on Bloom's taxonomy.

In addition, based on program-level rubrics in our literature review, we found that there are different challenges in engineering courses. So, this rubric would be customized by instructors based on their courses and design activities while instructors try to stick with the rubric's categories. As an example, a rubric for a design introduction project in a Biomedical Engineering junior level course has been provided in Table 4 in the Appendix. In this rubric, the instructor has used only design phases and criteria which are related to his course's learning objectives.

7. Conclusion, limitations, and future direction

In this work-in-progress study, we investigated design assessment tools and proposed a rubric that can be used across all programs in an engineering college. This rubric would provide a common design language across different engineering programs and allow each program to navigate their students design knowledge. Since this study is in progress, we are looking to gather feedback for the next steps which would be upgrading our rubric and collecting data to assess its reliability and validity. The final goal is to have a longitudinal assessment across several programs from the first-year engineering design to middle-year design and the senior design courses.

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Appendix

Table 1. *Search strings for databases used*

Database	Research strings	Date of search	Number of articles
Scopus	(TITLE-ABS-KEY ("Design skill" OR "Design knowledge") AND TITLE-ABS-KEY ("Assessment" OR "evaluat*" OR "rubric")) AND PUBYEAR > 2000 AND PUBYEAR < 2024 AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (AFFILCOUNTRY , "United States") OR LIMIT-TO (AFFILCOUNTRY , "United Kingdom") OR LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "Australia")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))	12/20/2023	219
ASEE	(TITLE-ABS-KEY ("Design skill" OR "Design knowledge") AND TITLE-ABS-KEY ("Assessment" OR "evaluat*" OR "rubric")) AND PUBYEAR > 2000 AND PUBYEAR < 2024 AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (AFFILCOUNTRY , "United States") OR LIMIT-TO (AFFILCOUNTRY , "United Kingdom") OR LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "Australia")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))	12/22/2023	79

Table 2. Rubric for assessing design skills

LOs	Design phase	Advanced	Accomplished	Developing	Beginner	Unacceptable
1	Problem Formulation	• Identifies the customer needs and gathers information about the user and product. • Not only frames the problem before suggesting ideas but also continuously reframes the problem across the design process. • Maps unknown assumptions and conjectures throughout the problem formulation.	Between (3) and (5)	• Identifies the customer needs but does not gather information about the user and product. • Frames the problem before suggesting ideas, but does not continuously reframe the problem across the design process. • Maps unknown assumptions and conjectures at the beginning of problem formulation.	Between (1) and (3)	• Does not identify the customer needs and does not gather information about the user and product. • Does not frame the problem before suggesting ideas. • Does not map unknown assumptions and conjectures in the problem formulation.
	Doing research and developing requirements	• Investigates similar products and prior solutions before moving to solutions. • Has a comprehensive understanding of criteria, constraints, and risks, and develops and refines them as needed.	Between (3) and (5)	• Only investigates similar products and prior solutions before moving to solutions. • Has a comprehensive understanding of criteria, constraints, and risks, but does not develop and refine them as needed.	Between (1) and (3)	• Does not investigate similar products and prior solutions before moving to solutions. • Does not have a comprehensive understanding of criteria, constraints, and risks.
	Idea Generation	• Uses brainstorming and divergent thinking to	Between (3) and (5)	• Uses a few representations or models that can	Between (1) and (3)	• Works with a limited number of ideas and does

		work on a variety of concepts. • Explains all the advantages and disadvantages of each design concept before choosing a design idea. • Considers comprehensive engineering standards and constraints that impact the use.		investigate the system's performance. • Performs a few experiments by changing only one variable in each experiment. • Considers a few engineering standards and constraints that impact the use.		not modify or discard them. • Makes design judgments without carefully analyzing all of the possibilities or focuses primarily on the advantages of the preferred concepts and the drawbacks of inferior ones. • Does not consider engineering standards and constraints.
	Prototyping and Evaluation	• Uses several representations or models to fully investigate the system's performance and explore the best design ideas that meet the requirements. • Performs several reliable experiments to gain knowledge about the systems and their components. • Carries out the design phases iteratively, where design concepts are refined repeatedly through feedback and techniques that are applied as many times as necessary, in whatever sequence.	Between (3) and (5)	• Uses a few representations or models that can investigate the system's performance. • Performs a few experiments by changing only one variable in each experiment. • Carries out the design with some iterations and refining the design concept once.	Between (1) and (3)	• Provides a model that does not support in-depth investigation of a system and would not be practical to implement. • Does not run experiments or run confounded tests by modifying several variables in just one experiment. • Carries out the design phases sequentially or carelessly just once without reflecting and learning from each design stage.

Table 3. Bloom's taxonomy and design phase points*

LOs	Bloom's Taxonomy	Design phase	Point

*We do not have data for this rubric yet. After collecting our data, we will have our final dataset in this table.

Table 4. Rubric for assessing discovery skills (BME)

LOs	Design phase	Advanced	Accomplished	Developing	Beginner	Unacceptable
Identifies clinical need Explores related biological and physical processes Logically frames problem and solution	Problem Formulation	• Identifies the medical need and gathers information about the issue. • Discusses biological and physical processes that are utilized. • Frames the problem before analyzing medical devices and continuously relates the solution to the problem. • Maps unknown assumptions and conjectures throughout the problem formulation.	Between (3) and (5)	• Identifies the medical need but does not gather information about the issue. • Discusses biological or physical processes that are utilized. • Frames the problem before suggesting ideas but does not continuously relate the solution to the problem. • Maps unknown assumptions and conjectures at the beginning of problem formulation.	Between (1) and (3)	• Does not identify the medical need or gather information about the issue. • Does not discuss biological and or discuss physical processes that are utilized. • Does not frame the problem before suggesting ideas or relating the solution to the problem. • Does not map unknown assumptions and conjectures in the problem formulation.

Identifies related work in the field Cohesively reviews scholarly articles and incorporates published work	Doing research and developing requirements	• Investigates similar products and researches alternate solutions before moving to conclusions. • Demonstrates a comprehensive understanding of published work related to the topic (criteria, constraints, risks)	Between (3) and (5)	• Only investigates similar products or researches alternate solutions before moving to conclusions • Demonstrates an adequate understanding of published work related to the topic (criteria, constraints, risks)	Between (1) and (3)	• Does not investigate similar products and does not research previous solutions before moving to solutions. • Does not demonstrate an understanding of related published work.
Identifies technology behind device functionality Concisely visualizes device interactions Identifies manufacturing methods	Idea Generation (Technical Analysis)	• Analyzes all of the following: measurement, actuator, control, and power systems along with data transmission and storage • Creates a complete block diagram visualization of most of the medical device interactions (i.e., sensor, battery, user, cloud, display) • Reviews manufacturing	Between (3) and (5)	• Analyzes some of the following: measurement, actuator, control, and power systems along with data transmission and storage • Creates a block diagram visualization of some of the medical device interactions • Reviews manufacturing technologies used to create the device but does not demonstrate	Between (1) and (3)	• Analyzes none of the following: measurement, actuator, control, and power systems along with data transmission and storage • Does not create a block diagram visualization • Does not review manufacturing technologies used to create the device or

		technologies used to create the device and demonstrates an understanding of material cost.		an understanding of material cost.		demonstrates an understanding of material cost.
Identifies legal requirements related to medical devices Identifies the change enabled Identifies the impact the medical technology	Prototyping and Evaluation (Usage / Impact)	• Discusses relevant rules and regulations related to the medical device • Investigates the treatment strategy and behavioral change that is enabled • Reviews the societal impact including all of the following: number of impacted people, where it is used, and what health impact is provided	Between (3) and (5)	• Discusses relevant rules or regulations for the use of the medical device • Investigates the treatment strategy or behavioral change that is enabled • Reviews the societal impact including some of the following: number of impacted people, where it is used, and what health impact is provided	Between (1) and (3)	• Does not discuss relevant rules and regulations • Does not investigate treatments strategies or behavioral changes • Does not review the impact of the medical device