Examining approaches to measuring trade-offs in design artifacts.

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Abstract - *(Work-in-Progress) One of the key features of engineering that differentiates it from science is trade-off decisions which affect the overall quality of a design artifact. Making trade-offs is a complex cognitive process that involves weighing possible outcomes against their respective benefits and costs in areas such as aesthetics, cost, degree of safety, and various performance indicators. Making trade-off decisions is an effective design practice, and is a key dimension of successful performance. Designers and design researchers have methods to assess design artifact quality. While useful, these methods are not necessarily easy to use nor do they indicate design competency. Moreover, they are not grounded in a definition of engineering design. The objective of this study was to complete a comprehensive review of design literature to synthesize common* ***tools*** *used by designers and design students to assess design artifact quality as well as* ***approaches*** *used to assess design quality, where trade-offs are inherently integrated into this decision-making to compare design process to design outcome measures. Results and visuals compare and contrast how these tools and approaches assess design artifacts in terms of: (1) encompassing multiple complementary and competing dimensions, (2) consistent and systematic application, and (3) design competency level communication. This work shows the common pitfalls in common design artifacts assessment tools and methods with respect to understanding a key design behavior, making trade-offs, and establishes the need for a comprehensive way to assess student designer trade-off decisions in design that are easy to use and conceptually grounded in a definition of engineering design.*

Index terms *- decision making, design competency, design education, engineering design, trade-offs*

I. INTRODUCTION

The quality of a design artifact has been characterized by the degree to which is addresses human technical, and economic dimensions [1] according to seminal engineering design textbook author Asimow. However, it is difficult to assess student design artifact where the range of "correct" answers is wide. Within an engineering context, design is "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" [1, p. 104]. Here, design involves attending to an interconnected system of non-negotiable (e.g., natural laws) and negotiable (e.g., social, political, economic, aesthetic, etc.) issues [2]. The degree to which a designer addresses all dimensions of the interconnected system and the resulting performance of the design constitutes the overall quality of a delivered design solution.

A need to better understand design quality has been recognized globally from both the design community and stakeholders in design projects [3] stemming from the concern that a lack of balancing trade-offs by instead focusing on reducing cost and time on projects could lead to a "loss of functionality and boring, unattractive design" [3, p. 319]. Gann and colleagues (2003)[3] note that measuring overall design quality presents major conceptual and practical problems despite the clear need for designers and researchers to be able understand the overall effectiveness of a final design artifact. Similarly, Atman, Adams, Cardella, Turns, Mosberg & Saleem [4] in comparing expert and novice designers' solution quality are transparent in issues and difficulty of quality assessment. They point out how techniques such as "holistic judgments by panels of experts, instructors, peers, and combinations thereof to rubrics that operationalize the specific dimensions that are assumed to represent quality" [5, p. 363] will affect the resulting evaluation.

Despite difficulties in measurement, designers and designer researchers have a need to understand design solution quality, and therefore tools that can serve this purpose. Many existing tools address multiple complementary and conflicting dimension to better understand design solution quality. In addition, many of the approaches attempt to be systematic. However, design quality measures can reduce quality to a single or small set of dimensions that are not fully representative of performance. Moreover, common mechanisms for quality measures such as panels and rubrics are typically limited to small number of cases, limit the ability to examine variation. Most importantly, these designer and researcher approaches to measuring solution quality are not necessarily aligned with informed design practice and therefore are unable to help students become more informed designers. This paper addresses the need for a measurement of design quality that encompasses many dimensions of performance.

II. Examining Approaches to Measure Design Artifact Quality

The following sections detail different approaches used to assess the *quality* of a design artifact with two different goals. When we refer to *quality* of a design, we mean the holistic, multidimensional value of a design. This definition of design quality extends beyond simply a focus on performance in a single area of the design artifact and represents how well a design solution addresses criteria and constraints while not sacrificing important needs. The first section gives a summary of current tools used by designers and design students to assess design artifact quality. The second section describes approaches to assessing design artifact quality for design research purposes to compare design process to design outcome measures.

A. Designer tools to assess design artifact quality

Designers in practice and design students have many methods available to assess the overall quality of their designs. These methods can be used in varying stages of the design process but are particularly common in ideation and iteration. The following section: (1) identifies common methods used to measure quality, (2) details how the methods evaluate quality, (3) explains the variables used in evaluation, and (4) describes the role of the final score in design phases of ideation or final evaluation.

One design tool, *A quality loss approach* [5], [6] to assessing design quality, particularly in assessing groups of design ideas during ideation and iteration cycles, is used in design practice and design education, as well as design research. In fact, using this tool in design began with Mitsubishi in the 1970s [6]. There are a variety of quality loss approaches, such as Taguchi methods, Quality Function Deployment (QFD), and House of Quality. Each offers a systematic and organized approach to make clear the relationships between manufacturing functions and customer satisfaction in an easy to visualize manner. These performance goals are not prescribed within the tool, and those who use these tools often identify issues that span technical, economic, and human dimensions. To use this approach, performance goals are represented in a matrix form that lists each customer requirement that will be rated (often on a scale of 1-5) as the "whats" and each technical requirement that will be rated similarly as the "hows". Then, qualitative comparisons across multiple and potentially competing technical performance and customer attributes can be made. When using these tools during the ideation phase of design, the focus is often on comparing a set of alternatives to choose an option (or combination of options) that has the most promise. For use during iterative improvement cycles, the focus is often on ways to monitor and optimize solution performance. Overall, the premise of a quality loss approach asserts that "good" design is robust and less sensitive to uncontrollable factors in both manufacturing and use [7]. The "quality score" produced is a numerical representation of how well a solution meets customer priorities and engineering specifications in relation to other design options.

Another designer tool features a mathematically-grounded approach to assessing the quality of a design concept, *Axiomatic Design* [8]. This method is often used in assessing designs at the ideation and "optimization" or iteration phase. The premise of this framework is the relationship between the customer domain (CAs), functional domain (FRs), physical domain (DPs) and process domain (PVs). In Axiomatic Design Theory, a designer should strive to maintain the independence of the functional requirements while minimizing the information content of the design, where information content is related to the probability of success of a particular FR and DP design concept. A key strength of using this approach to assess a design is that it allows a systems perspective, with sets of interrelated criteria in a repeatable manner. However, this predominantly conceptual approach is difficult to use and interpret, especially in more complex design situations [8]. This approach does not result in a final score or overall ranking of design alternatives, but instead can identify internal technical conflicts.

A third tool used by both designers in practice and student designers are *Decision Matrices* (e.g. Pugh Decision Matrices [9]), which make risks in design alternatives visible by explicitly comparing strengths and weaknesses between designs. While this tool can be used at any stage of the design process, it is typically employed at the ideation stage. The designer will develop a list of criteria and assigns a score to each criterion of each alternatives. An important distinction for Decision Matrices as opposed to QFD and House of Quality approaches is that there are no weightings of criteria as this method is based on simple ratings (e.g., yes/no/maybe) or comparative ratings (e.g., better than the other options, same, or worse). Categories for evaluation are not pre-defined in this tool, but typically include effectiveness, feasibility, capability, cost, and time. This tool allows evaluation and prioritizing a list of options through a numerical, ordinal representation from a group of designs or options.

A final approach to be discussed, *metrics for measuring ideal effectiveness* [10], is meant to assess ideation effectiveness through the following sub-scores: quantity, quality, novelty and variety within a set of ideas. It is typically used for evaluation of groups of ideas. Quality is seen as an estimated measure of the degree to which a design idea met design specifications and was feasible. This broad view of quality refers specifically to conceptual design and was not developed to assess final design solution quality. In determining quality, one particular design has to serve as the baseline comparison for other designs. This can make the measurement approximate and cognitively difficult.

Each of these methodological approaches for assessing design quality are typically employed at the ideation stage or conceptual design. As such, they can provide early insights into how a design solution may perform or underperform that can be addressed through iterative cycles. Therefore, these approaches can be effective formative assessments for students, providing feedback as students progress through the design process. A strength of these methods is that they provide a framework to explicitly make both benefits and risks (or advantages and disadvantages) of the design visible to the design decision-maker. Although these approaches are generally classified as designer tools, the extent to which each is used within design education varies. In a review of fourteen commonly used engineering design textbooks used in first-year engineering, [11] found that tools to assist in understanding design quality, specifically for decision-making, are mentioned only briefly or as an ancillary step in the design process in half of the textbooks. In reviewing five of the cited textbooks from their study [12]–[16] plus an additional two influential texts [9], [17], we found *decision matrices* and *quality loss approaches* (House of Quality) are explicitly referenced as design tools.

Table 1 (Appendix A) summarizes these designer tools used to assess design solutions across dimensions of: (1) ability to reflect multiple complementary and competing dimensions with an explicit focus in referencing Asimow's [1] three areas of technical, human, and economic trade-offs, (2) application consistency, (3) ease of use, (4) design phase used in, (5) tool audience (designer or researcher), (6) indicative of design competency, and (7) use of method in design education.

All of the designer tools to assess quality in Table 1 address multiple complementary and competing dimensions, although none of them necessarily prescribe human, technical and economic dimensions. A common strength across all approaches is that they are systematic, but a common weakness is that they may not be easy to use. All approaches can be useful in the ideation and optimization phases, and can be useful in providing feedback to the designer, so they have potential utility as a formative assessment. Decision matrices and decision analysis methods can also be used in final artifacts and have some utility as summative assessments. Collectively, all of these types of tools allow comparisons of design ideas or solutions in a visual way. However, it is only through the use of these tools that we can get a sense of student design competency.

B. Design researcher tools to assess design artifact quality

In design research literature, the role of a quality score for student design outcomes is often used to explore correlations between outcomes and design processes or behaviors [4], [18]–[22]. These key empirical studies utilize an expert judge or set of scorers to determine a quantitative quality score for a design artifact. The following sections detail two types of quality assessments: assessment of the design solution itself and assessment of design documents through research papers that illustrate these assessment types. In both types of design researcher assessments, the researchers use a rubric to evaluate the solution or documentation, and follow a procedure to convert the qualitative solution/documentation to a quantitative measure. Oftentimes, there is an explicit effort to calibrate scores through interrater reliability.

Researcher evaluation tools to assess design solutions can be systematic, especially with documented and well-understood rubrics. One such systematic approach used a detailed rubric to assess the quality of final design solutions to address a playground challenge in several studies with undergraduate engineering students and experts [4], [18], [23][24]–[27]. In these studies, the research team served as expert judges, following the rubric and ranking each design. They made pairwise comparisons between all possible pairs of design solutions and assessed inter-grader reliability for consistent scoring. A constant sum algorithm, a scaling technique that involves the assignment of a fixed number of units to each rubric element, was applied to arrive at the set of relative weights, and to be normalized to a score of one. The rubric addressed each design's ability to meet design criteria explicitly specific to the design task (playground). Because this comprehensive rubric included playground principles such as safety standards for particular playground equipment, it is not a generalizable rubric. The final score, "quality of design solution score" represented how well students addressed design criteria and this score was correlated with other measures of undergraduate engineering student design processes.

Another type of research focuses on the *assessment of design documents*. In one such study, Dong and colleagues [28] calculated what they termed an “outcome quality” of final solutions as described in written reports from teams of graduate students in their “document analysis method for characterizing design team performance” [28]. Two researchers used a rubric to evaluate the designs. The rubric consisted of 13 categories, including mission statement, user scenarios, customer and user needs, and concept sketches. Researchers assigned a score of 1 (worst) to 5 (best) to each category, resulting in a final ordinal ranking. This final ranking of design outcome was used for further statistical analysis to correlate design quality with levels of semantic coherence in design documents.

A third type of research focuses on the *assessment of design solutions and design outcomes*. In an example of this time of assessment, Yang[20]–[22] studied undergraduate engineering students and measured “design outcome” as quality of a final design solution of a prototype in two ways [20]–[22]. The first method was an individual final grade, given based on class assignments and a design logbook. The second method was each team’s final ranking in the design contest, based on the number of rounds that the team was able to win. Design outcome score was used to perform statistical analysis with prototype characteristics such as level of simplicity and time spent making the prototype.

Table 2 (Appendix A) summarizes these design researcher tools used to assess design solutions across dimensions of: (1) ability to reflect multiple complementary and competing dimensions with an explicit focus in referencing Asimow’s [1] three areas of technical, human, and economic trade-offs, (2) application consistency, (3) ease of use, (4) design phase used in, (5) tool audience (designer or researcher), (6) indicative of design competency, and (7) use of method in design education.

Research methods to assess design quality do not explicitly indicate design competency but are often used to *understand* relationships or correlate with design competencies and behaviors. There are, however, limitations in research tools used to assess design. One such limitation is the understandable subjectivity in raters that could result in assessment due to personal philosophies and values, causing the experts to weigh certain elements differently (even when using a rubric, as experts likely have to balance trade-offs within the rubric). Incorporating subjective characteristics in design solution evaluations is important and a key component of fields such as product design in understanding consumers’ perceptions of elements such as ease of use [29] or ergonomics [30]. However, collection and analysis of these subjective measurements requires a systematic approach. In addition, finding experts for a particular area and crediting them with “expert” status can be difficult. In general, because this group of assessment approaches requires a thorough review of the design and all associated data and design features, they are not easily scalable to large classrooms without the burden of excessive time.

III. Opportunity for New Perspectives in Measuring Design Quality

Despite the relevance and need for a measurement of design quality, it is easy to understand some of the limitations in current approaches of measuring quality of student design solutions. While all of these approaches address multiple dimensions, none explicitly are guided by Asimow’s depiction of human, technical, and economic dimensions. In addition, all of these methods can be applied consistently, but they vary drastically in ease of use from simple to overtly complex. Most importantly, with the exception of decision matrices, none of these methods are explicitly indicative of a design competency of balancing trade-offs. There is a gap in the literature for a quality assessment protocol for use by both designers and designer researchers.

IV. Future Work & Implications

This work-in-progress shows the common pitfalls in common design artifact assessment tools and methods with respect to understanding a key design behavior, making trade-offs. In doing so, this paper illustrates the need for a measurement protocol that allows for a comprehensive way to assess student designer trade-off decisions in design that can be applied consistently and systematically while maintaining ease of use. Ongoing work will test different protocols to address this gap in the literature while studying their overall utility in differing populations.

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Appendix A – Summary Tables

Table 1. Summary of dimensions in design

Dimensions	Quality loss	Axiomatic design	Decision matrices	Metrics for measuring ideation (Shah et. al, 2003)
Addresses multiple complementary & competing dimensions	●	●	●	●
-Technical	◌	●	◌	○
-Human	◌	◌	◌	○
-Economic	◌	●	◌	○
Applied consistently	●	●	●	●
Indicative of design competency	◍	◍	●	◍
Easy to use	◍	○	●	◍
Applicability in different settings/generalizable	●	●	●	●
Design phase:				
-Ideation or Optimization	●	●	●	●
-Final/Prototype	○	○	●	○
Formative assessment	●	●	●	●
Summative assessment	○	○	●	○
Tool audience:				
-Designer tool	●	●	●	●
-Researcher tool	○	○	○	●
Used in design education	●	◍	●	◍

Key: ● = yes, ○ = no, ◍ = sometimes

Table 2. Summary of dimensions in researcher tools used to assess quality

Dimensions	Assessment of design solution (e.g. Playground Rubric by Atmen et al.)	Assessment of design documents (e.g. Document analysis method by Dong et al.)	Assessment of design solution & documents (e.g.Yang prototype design outcome)
Addresses multiple complementary & competing dimensions:	●	●	●
-Technical	◍	◍	●
-Human	◍	◍	○
-Economic	●	●	○
Applied consistently	●	●	●
Indicative of design competency	◍	◍	◍
Easy to use	●	●	●
Generalizable	○	○	○
Design phase:			
-Ideation or Optimization	○	○	○
-Final/Prototype	●	●	●
Formative assessment	○	○	○
Summative assessment	●	●	●
Tool audience:			
-Designer tool			
-Researcher tool	●	●	●
Used in design education	○	○	○

Key: ● = yes, ○ = no, ◍ = sometimes