2021

Understanding Informed Design through Trade-Off Decisions With an Empirically-Based Protocol for Students and Design Educators

Molly H. Goldstein

University of Illinois, Urbana-Champaign, mhg3@illinois.edu

Robin S. Adams

Purdue University, rsadams@purdue.edu

Senay Purzer

Purdue University, purzer@purdue.edu

Follow this and additional works at: <https://docs.lib.purdue.edu/jpeer>

Recommended Citation

Goldstein, M. H., Adams, R. S., & Purzer, S. (2021). Understanding Informed Design through Trade-Off Decisions With an Empirically-Based Protocol for Students and Design Educators. *Journal of Pre-College Engineering Education Research (J-PEER)*, 11(2), Article 3.

<https://doi.org/10.7771/2157-9288.1279>

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

This is an Open Access journal. This means that it uses a funding model that does not charge readers or their institutions for access. Readers may freely read, download, copy, distribute, print, search, or link to the full texts of articles. This journal is covered under the [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).

Understanding Informed Design through Trade-Off Decisions With an Empirically-Based Protocol for Students and Design Educators

Abstract

Trade-off decisions, which necessitate striking a balance between two or more desirable but competing features, are a crucial part of design practice. However, they are known to be difficult for student designers to make. While designers, educators, and researchers have numerous methods to assess the quality of design artifacts, 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 objectives of this study were twofold. First, we developed a protocol to depict design artifact quality through the lens of design trade-off decisions. We aimed to produce a protocol that: (1) encompasses multiple complementary and competing dimensions, (2) can be applied consistently and systematically, and (3) indicates design competency. We conceptualized a quantitative representation of the degree to which a design artifact addresses human, technical, and economic requirements called the *Trade-off Value Protocol*. Second, we tested the *Trade-off Value Protocol* by applying it to 398 middle school students' design artifacts of energy-efficient homes. We used an etic approach of thematic analysis to identify the patterns of variation therein. We found *five distinct patterns of variation* in the set of student design artifacts, which suggested certain trends in the way that students address design dimensions and demonstrate varying levels of design competency. The *Trade-off Value Protocol* isolates an important feature of design competency with which beginning designers often struggle and could be a tool for educators to help students become more informed designers.

Keywords

decision making, design cognition, design quality, engineering design, informed design, trade-offs

Document Type

Research Article

Journal of Pre-College Engineering Education Research 11:2 (2021) 25–41

Understanding Informed Design through Trade-Off Decisions With an Empirically-Based Protocol for Students and Design Educators

Molly H. Goldstein¹, Robin S. Adams², and Senay Purzer²

¹University of Illinois, Urbana-Champaign

²Purdue University

Abstract

Trade-off decisions, which necessitate striking a balance between two or more desirable but competing features, are a crucial part of design practice. However, they are known to be difficult for student designers to make. While designers, educators, and researchers have numerous methods to assess the quality of design artifacts, 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 objectives of this study were twofold. First, we developed a protocol to depict design artifact quality through the lens of design trade-off decisions. We aimed to produce a protocol that: (1) encompasses multiple complementary and competing dimensions, (2) can be applied consistently and systematically, and (3) indicates design competency. We conceptualized a quantitative representation of the degree to which a design artifact addresses human, technical, and economic requirements called the *Trade-off Value Protocol*. Second, we tested the *Trade-off Value Protocol* by applying it to 398 middle school students' design artifacts of energy-efficient homes. We used an etic approach of thematic analysis to identify the patterns of variation therein. We found *five distinct patterns of variation* in the set of student design artifacts, which suggested certain trends in the way that students address design dimensions and demonstrate varying levels of design competency. The *Trade-off Value Protocol* isolates an important feature of design competency with which beginning designers often struggle and could be a tool for educators to help students become more informed designers.

Keywords: decision making, design cognition, design quality, engineering design, informed design, trade-offs

Introduction

In design, the decision-making process requires designers to consider trade-offs, that is, choices that necessitate striking a balance between two or more desirable but often competing criteria. In design, trade-off decisions are unavoidable because design problems are contextualized and constrained, and exist at the intersection of social and technical issues (Gabbay et al., 2009). Design also involves attending to an interconnected system of non-negotiable issues (e.g., natural laws) as well as negotiable ones (e.g., social, political, economic, aesthetic, etc.) (Goel & Pirolli, 1992). To achieve a form and function that meet clients' objectives and/or users' needs, engineers must make decisions through a systematic, intelligent process (Dym et al., 2005, p. 104). Hence, the quality of a designed system does not point to a "perfect" answer, but instead to a negotiated design that is deemed to satisfy the requisite conditions.

Cultivating design thinking in K-12 education is imperative to developing global citizens who are able to make decisions effectively. Trade-off decisions represent a promising path to honing those critical thinking skills. However, although

scaffolding trade-off decisions in design education is important, it also has proved difficult. We argue that students' decision-making, as a cognitive process, is manifested in their designed artifacts (objects, systems, processes). As such, a better understanding of students' artifacts allows educators to understand students' intentions better and help guide them to improve their design reasoning.

Therefore, in this study, we explore pre-college students' design artifacts to understand and categorize the cognitive processes they use to make trade-off decisions. The objectives of this study were twofold. First, we aimed to develop a method to depict design artifact quality through the lens of design trade-off decisions with a protocol that: (1) encompasses multiple complementary and competing dimensions, (2) can be applied consistently and systematically, and (3) is indicative of design competency. Our second objective was to test our protocol (*Trade-off Value Protocol*) as a means to assess patterns of quality variation in students' artifacts and, in so doing, to better understand the transferability of this protocol to other design settings that include both subjective and objective criteria.

Literature Review

Importance of Trade-Offs in Engineering Practice

Trade-offs are inherently part of engineering design. As was established several decades ago, engineering design draws on a "synthesis of technical, human, and economic factors; and it requires the consideration of social, political, and other factors whenever they are relevant" (Asimow, 1962, p. 2). Here, *human* encompasses what humans want, *technical* refers to technical performance (often expressed through scientific and mathematical concepts), and *economic* refers to monetary costs. While all of these areas of design are important, the level of emphasis on each can be quite subjective, leading to variations in the process and conclusion of trade-off decision-making. On a global scale, both the design community and stakeholders in design projects have recognized the need to understand trade-off decisions better (Gann et al., 2003). This awareness has arisen 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" (Gann et al., 2003, p. 319).

One of the key dimensions of design performance is making trade-offs, which is also an indication of design competency (Crismond & Adams, 2012). When working through trade-off decisions, professionals consider the benefits and pitfalls of different design alternatives as part of their design thinking and decision-making (ITEA, 2000). Akin and Lin (1996) describe this as a process of "honeycombed" decisions. For example, in a study of automotive design engineers, Thurston (1991) demonstrated the many decisions that were involved in material selection for the structural frame of a car. In evaluating alternative materials alone, the design team needed to consider weight, corrosive resistance, flexibility, and manufacturing options. Likewise, designers work through complex and ill-structured problems that require them both to weigh options and to forecast the impact of their decisions (Strobel & Pan, 2010). Making design trade-off decisions is complex in engineering practice.

Engineering Design Trade-Offs in the Pre-College Classroom

Since design is so critical to the engineering profession, it has been made a core focus in college-level engineering education through accreditation criteria (Accreditation Board for Engineering and Technology, 2019). Design is also becoming a more common feature of K-12 education. A 2012 report from the National Academies of Sciences, Engineering, and Medicine, titled *A Framework for K-12 Science Education*, proposed integrating engineering with science education (National Research Council [NRC], 2012). The Next Generation Science Standards (NGSS) followed suit, further elucidating the connection between engineering, design, and science education for K-12 students (NGSS Lead States, 2013). The *Framework* defines the role of trade-offs as part of a disciplinary core idea: optimizing the design solution.

Optimization often requires making trade-offs among competing criteria. For example, as one criterion (such as lighter weight) is enhanced, another (such as unit cost) might be sacrificed (i.e., cost may be increased due to the higher cost of lightweight materials). In effect, one criterion is devalued or traded off for another that is deemed more important. When multiple possible design options are under consideration, with each optimized for different criteria, engineers may use a trade-off matrix to compare the overall advantages and disadvantages of the different proposed solutions. The decision as to which criteria are critical and which ones can be traded off is a judgment based on the situation and the perceived needs of the end-user of the product or system. Because many factors—including environmental or health impacts, available technologies, and the expectations of users—change over time and vary from place to place, a design solution that is considered optimal at one time and place may appear far from optimal at other times and places. Thus different designs, each of them optimized for different conditions, are often needed. (NRC, 2012, p. 209)

Through the implementation of these standards, design is quickly becoming a focus for increasingly younger students. Moreover, decision-making at the K-12 level is an essential component of problem-solving abilities, which are important for making science connections (Purzer et al., 2015). Broadly enhancing problem-solving abilities through engineering design will better prepare students for additional science, technology, engineering, and mathematics (STEM) education and will have positive implications for the future STEM workforce. Additionally, understanding how pre-college students approach design, including cognitive practices such as making design trade-off decisions, would result in better design education at the pre-college level and beyond.

Evaluating Student Trade-Offs

Because trade-off decisions are a crucial part of engineering design, with engineering design taught in pre-college settings, evaluating these trade-offs is an important pedagogical problem and research opportunity. Although it is difficult to measure, students, educators, and researchers need to understand design solution quality, and thus need tools that can help them do so. As scholars have pointed out, little is known about how high school students currently use decision-making processes in design (Lammi et al., 2018). Many existing tools and strategies typically employed at the college level and beyond address multiple complementary and conflicting dimensions to analyze design solution quality. In a review of fourteen popular engineering design textbooks used in first-year courses, Purzer and Chen (2010) found that in half of these textbooks 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 reviewing five of the textbooks cited in their study (Brockman, 2009; Dieter & Schmidt, 2009; Dym et al., 2009; Niku, 2009; Oakes et al., 2006) plus an additional two influential texts (Cross, 2008; Pugh, 1990), we found *decision matrices* and *quality loss approaches* (e.g., House of Quality) explicitly referenced as design tools.

In a review of design decision-making tools for designers and researchers, Goldstein et al. (2020) discuss the utility of decision matrices. Decision matrices (e.g., Pugh, 1990) allow students to address multiple complementary and competing dimensions by making risks in design alternatives visible and by explicitly comparing strengths and weaknesses between designs. While these tools can be used at any stage of the process, they are typically employed in conceptual design. The designer will develop a list of criteria and assign a score to each criterion of each alternative. Categories for evaluation are not predefined but typically include effectiveness, feasibility, capability, cost, and time. These tools allow the designer to evaluate and prioritize a list of options through a numerical, ordinal representation from a group of designs or options. However, these tools do not necessarily indicate design competency (Goldstein et al., 2020).

While students typically use design tools in earlier stages of conceptual design, educators often need to understand design quality, and therefore trade-offs, in final design artifacts. In this sense, educators aim to assess how well a student addressed a design challenge and/or demonstrated mastery of related learning outcomes. It is difficult and time-consuming to understand or assess an individual *design process*, especially in the pre-college classroom. Asunda and Hill (2007) suggest that using design artifacts for evaluative purposes might help educators better understand *both the design products and process* of their students. Despite recent calls for improvement in STEM education (National Academy of Engineering [NAE] & NRC, 2009, 2014; NRC, 2011, 2012), assessment tools are still sparse, with existing assessments focusing on knowledge within a single STEM discipline (NAE & NRC, 2014). According to the NAE, “they typically focus on content knowledge alone and give little attention to the practices in the disciplines and applications of knowledge” (NAE & NRC, 2014, p. 6), which is not helpful in improving young students’ design competency. Because design challenges are numerous, there is no one way to assess a final design artifact, which means that educators often rely on their own rubrics (Lammi et al., 2018). However, assessing engineering design challenges is a complicated task (Lammi et al., 2018) in which educators might struggle with both subjectivity and scalability. In fact, Lammi et al. (2018) highlight understanding what assessment is appropriate for open-ended challenges and how open-ended problems can be assessed in a timely manner as two areas needing additional research.

In addition to design students’ and educators’ need to evaluate design artifacts, design researchers are often interested in assessing an overall quality score for participant design outcomes to explore correlations with and between processes or behaviors (Atman et al., 2005, 2007, 2008; Cardella et al., 2008; Dong et al., 2004; Yang, 2003, 2005, 2009). Yet the research tools used to assess design quality have clear limitations. One such limitation is the understandable subjectivity in ratings due to raters’ personal philosophies and values, causing raters to weigh elements differently even when using a rubric. Incorporating subjective characteristics in evaluating design solutions is important and is a key component of product design for understanding consumers’ perceptions of qualities such as ease of use (Lan et al., 2008) or ergonomics (Demirel & Duffy, 2017). However, collection and analysis of these subjective measurements require a systematic approach. In addition, finding assessors 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.

This article introduces a new metric for assessment that we call the *Trade-off Value Protocol*, which addresses the need for a measurement of design solution quality that encompasses many dimensions of performance and can be useful in education and research.

Theoretical Framework

The Trade-off Value characterizes this key issue of multiple complementary and competing values. As shown in Figure 1, Asimow's (1962) characterization of the distinct dimensions in engineering design is a guiding principle of the Trade-off Value, defined as the extent to which a design artifact addresses these complementary and competing dimensions. A design artifact with a high Trade-off Value embodies a systems approach to design, allowing us to consider the competing dimensions rather than focusing solely on optimizing one or two of the dimensions. Figure 1 demonstrates the overlap of the dimensions as the Trade-off Value. This idea complements current frameworks, such as the IDEO model of human-centered design, which emphasizes the intersection of desirability, feasibility, and viability (Brown, 2009) for innovation. As the *Trade-off Value Protocol* is complementary to other existing frameworks, it may be broadly useful to designers and design educators.

Designers are required to make decisions to define the solution space as well as decisions to characterize the problem space (Dorst, 2006) including considerations of conflicting users' needs (Crismond & Adams, 2012). Because design is wrought with decisions, engineering designers must demonstrate competent decision-making in design trade-offs. Through the design process, informed designers "use words and graphics to display and weigh both benefits and tradeoffs of all ideas before picking a design" and are skilled at "weighing and articulating" (Crismond & Adams, 2012, p. 761) both the pros and cons of a particular design, looking for trade-offs in even the best ideas. Making design trade-off decisions is a cognitive process that can be classified as what Hay et al. (2017) describe as a primarily executive function involving concept evaluation, decision-making, and reasoning.

Student designers lack the same understanding of design that experts or informed designers have in many areas, including making design trade-off decisions. In summarizing studies of student designers, Crismond and Adams (2012) emphasize that they tend not to weigh all of their options before making a decision. In fact, they may be "oblivious to the unavoidable tensions and trade-offs" (Crismond & Adams, 2012, p. 761). Furthermore, when describing a design decision, they are apt to cite only a pro of the chosen design or a con of a passed-over design (Crismond & Adams, 2012) such as referencing high cost as a negative aspect or energy efficiency as a positive aspect. Because making trade-offs is such a crucial skill for practicing engineers, design artifacts that indicate effective trade-offs might suggest a level of design competency. However, as mentioned earlier, educators would benefit from a consistent rubric through which to appreciate it.

While working on a project directed towards a net-zero-energy home using a computer-aided design platform, Energy3D, we developed a protocol to calculate design quality that we believe demonstrates consistency and ease of use, presents a systems approach to addressing multiple dimensions, and represents a grounding in design competency. We tested the *Trade-off Value Protocol* in a middle school classroom with 398 students to determine if this method does, in fact, accomplish those three goals. Through the analysis of student cases, we identified meaningful variations in how students addressed multiple design dimensions and exhibited design competency.

Figure 1. *Trade-off Value Protocol* conceptual framework.

Methods

Participants and Design Challenge

This study was conducted with 398 students aged 12–14 years at two middle schools in the Midwestern United States in the spring of 2017. The design challenge, which was presented as part of the science curriculum at both schools, asked students to individually design an eco-friendly home by coming up with three unique designs that would consume minimal energy over the course of a year within specific criteria and constraints (see Table 1). The exercise involved using the Energy3D software to design single-family homes. Students were instructed to create high-quality house designs that attempted to balance energy consumption, construction cost, livability, and aesthetics. The systems thinking required in the design project exemplified trade-off decisions, as students were tasked with designing a home with complementary and conflicting criteria that were technical, human, and economic. This was an authentic problem-solving experience for students, which included multiple, conflicting goals with competing criteria (Jonassen et al., 2006).

Data Sources and Collection

This research was conducted in large part using a free, open-sourced computer-aided design platform, Energy3D (<http://energy.concord.org/energy3d/>), which allows students to design and build energy-efficient buildings. This software is very user-friendly and was developed with educational research purposes in mind (Xie et al., 2018). As students design in Energy3D, a logger collects their process data or log data behind the scenes (i.e., all user interactions with the software). In addition to fine-grained log data (such as edit window, add solar panel, etc.), Energy3D records design specifics for the final design. The following performance data were recorded in Energy3D from the final design artifact for each student: (1) total annual energy consumption, (2) total construction costs, (3) approximate volume of home, (4) total area of all windows of home, (5) total area of all walls of home, and (6) total number of satisfied constraints out of a possible eight. These data speak to the three dimensions of the framework (as shown in Table 2). Additionally, Energy3D contains a built-in electronic journal, so that students can reflect as they design and answer design prompts.

Students saved final versions of their home design in Energy3D electronically. These files were opened in Energy3D by the research team to view the aesthetics of the final design and run analyses of the final construction costs and annual energy consumption. Thus, this design artifact file allowed both a high-level look at how well a student approached the design task as well as a very detailed look at how students address specific design criteria and constraints. Students were encouraged to create three unique concepts for their design and were free to choose when to start working on one design or another. Students used the Energy3D electronic journal to state which design iteration they deemed “best,” and were prompted to explain their rationale.

Data Analysis

Quantitative Stage: Trade-off Value Protocol

The *Trade-off Value Protocol* includes the following steps: (1) set parameters to measure human, technical, and economic design features, (2) categorize metrics to identify the aforementioned design features, (3) compute percentile ranks of each dimension, and (4) total each dimension’s value to find the total Trade-off Value. Table 2 summarizes how the log data, generated within the Energy3D system, were mapped to the Asimow (1962) characterization of engineering design.

Table 1
Design challenge criteria and constraints.

Criteria	<ul style="list-style-type: none"> Minimize energy consumption (meaning the building can reach zero or negative annual net energy) Minimize total cost of the building Comfortably fit a 4-person family (approximately 2200 ft² or 204 m²) Has an attractive exterior and is desirable
Constraints	<ul style="list-style-type: none"> Cost cannot exceed \$250,000 in building materials Each side of the house must have at least one window Do NOT add more than 40 solar panels (regardless of their conversion efficiency) Keep the room temperature of the house at 20°C all the time The house’s platform must not exceed the 28 m × 36 m platform provided in the software Tree trunks must be outside the house Only 1 structure on the platform (no doghouses, detached garages, etc.) There is no need to design any interior structure such as rooms, floors, or stairs

Table 2
Trade-off framework with associated log data.

Engineering dimensions	Representative log data
Technical	- Total annual energy consumption per volume (energy/volume) - Number of satisfied constraints in Table 1 (out of a possible 8)
Human	- Total area of all windows and walls of home (e.g., “livability” as demonstrated through window-to-wall ratio for the house)
Economic	- Total construction costs (cost/volume)

As shown here, some calculations (e.g., volume of home) speak to multiple criteria, demonstrating system inter-relationships among the size of the house, energy consumption, and total construction cost.

Student performances within each of these trade-off dimensions were converted to a percentile rank, ensuring that the rank order is logical following calculations presented in Equation 1 (e.g., a high construction cost is undesirable along the economic dimension and would result in a lower percentile rank, while a high window-to-wall ratio is desirable along the human dimension and would result in a higher percentile rank). Data normalization as a percentile rank provides an equivalent basis for comparison as percentile rank describes the percentage of values in a specified distribution that fall at or below the value of interest (Privitera, 2015). This normalization method was chosen because it corrects for range differences in a solution space as well as differences in the mean and standard deviation by parameter design task. Each percentile rank corresponds to a number out of 100.

Finally, the composite Trade-off Value was calculated as the sum of the percentile ranks of human dimensions, technical dimensions, and economic dimensions, as shown in Equation 1.

$$\begin{aligned}
 \text{Trade-off Value} = & \sum_i \text{ilerank}(\text{Human factors})_i + \\
 & \sum_j \text{ilerank}(\text{Technical factors})_j + \\
 & \sum_k \text{ilerank}(\text{Economic factors})_k
 \end{aligned}
 \quad (\text{Equation 1})$$

The maximum score is a function of the number of trade-off dimensions involved in a particular design context and is flexible to represent all design contexts due to differing priorities in unique situations. A key requirement of the *Protocol* is the ability to quantitatively assess student design performance within a set of designs to calculate each percentile ranking.

Applying the *Trade-off Value Protocol* to this particular design challenge within Energy3D involved making some decisions to best represent student design data. We calculated the energy per volume and cost per volume for each design to allow these parameters to speak to the overall efficiency of the building rather than just the straight cost or energy usage. We represented livability through a calculation of the window-to-wall ratio, consistent with the key feature experts deemed important in a similar design project assessment (Goldstein et al., 2016). Each of the four design performance data from Table 2 (i.e., energy/volume, number of met constraints, window-to-wall ratio, and cost/volume) were converted to a percentile rank within the sample.

The maximum score of 400 is a function of the number of trade-off dimensions involved in this particular design context and is not meant to represent all design contexts due to differing priorities in each situation. However, the theoretical framework that distinguishes between human, technical, and economic dimensions is quite transferable to other design settings with both subjective and objective values and is consistent with our theoretical framework (Asimow, 1962). Two technical dimension measurements have been accounted for in Equation 1: energy per volume and the degree to which constraints were met. These two variables comprise the technical dimensions component while the economic and human dimensions are represented through one numeric measurement. Although the calculation accounts for two measurements of the technical aspects of the design, these sub-calculations represent two unique performance aspects of the design artifact: energy consumption and attention to design constraints. Adding a fourth dimension to the *Trade-off Value Protocol* would not have followed the theoretical framework, affecting both teaching and learning. Another option to address design artifacts that do not meet constraints is to eliminate them from the calculation. While that might be an acceptable method for design research, it would be far less useful in the pre-college classroom, where students are learning to engage in design and must be able to make and learn from mistakes. Including constraints as part of the technical dimension allows for transferability of the *Protocol* to other design settings; that is, if a design challenge does not specify constraints, the equation will not include this dimension.

Qualitative Stage: Thematic Analysis

After calculating a Trade-off Value for each student's design artifact, we took an etic approach to analyze the collective group of student design artifacts thematically and discover patterns in the students' approaches to the design challenge. In a pile-sort activity (for more detail, see Goldstein et al., 2016), the first author analyzed the entire sample to better understand the ways that design artifacts might represent students' design strategies. The first author reviewed single-page printed summaries for each student design artifact that included two pictures of the house and a table with a summary of all dimensions included in the *Trade-off Value Protocol* (i.e., energy/volume, constraints met, window-to-wall ratio, and cost/volume and the corresponding percentile rank of each dimension). Five themes emerged and were discussed with the research team. Then, the first author and a research assistant independently categorized 20% of the students' design artifacts to establish inter-rater reliability. The inter-rater reliability (Miles & Huberman, 1994) or percent agreement was 71 out of 80 (89%). The two researchers reached consensus on the nine disagreements before the first author continued thematically analyzing the remaining design artifacts. This analysis allowed a glimpse into the degree to which students grappled with trade-offs in their design process and makes visible the cognitive process of making trade-off decisions.

Results and Discussion

The overarching goal of this study was to better understand and evaluate informed design practices among student designers. One key informed design behavior, making trade-offs, served as the lens for developing a protocol to calculate design artifact quality that: (1) encompasses multiple complementary and competing dimensions, (2) can be applied consistently and systematically, and (3) is indicative of design competency. Through analysis of 398 students' design data, we demonstrate how the *Trade-off Value Protocol* addresses these three requirements. We calculated a Trade-off Value score for each student at both schools. Because the Trade-off Value is calculated as a percentile rank of performance relative to a group, the Trade-off Values were computed independently for each school.

This section presents patterns of variation observed through a close examination using the *Trade-off Value Protocol*. After calculating a Trade-off Value for each student's design artifact, we took an etic approach to analyze the collective group of student design artifacts thematically, which allowed us to discover patterns. An etic approach in qualitative research, sometimes called a deductive approach, makes use of conceptual categories and disciplinary knowledge to understand data (Monteagut, 2017). This analysis involved looking at each design artifact and its Trade-off Value to uncover scenarios in which the designer focused on a single dimension (i.e., energy, cost, aesthetics) and approaches of considering many dimensions. In doing so, we identified five distinct patterns of variation in artifact quality, which suggests that the ways students address multiple complementary and conflicting design dimensions can be appreciated better through pattern-based organization. The Trade-off Value makes visible patterns of multiple dimensions collectively balanced versus a focus on a single dimension, whether technical, human, or economic.

Table 3 illustrates five trade-off decision patterns by detailing the five student approaches to addressing the design challenge. It also contains a representative student artifact and corresponding radar or spider chart detailing the performance contribution of each dimension (i.e., energy, cost, aesthetics, and the degree to which constraints were met) to the Trade-Off Value as well as a description of the artifact performance. The combination of the total Trade-off Value as well as performance along each dimension allows a holistic understanding of artifact performance. This table shows both energy and constraints met separate in the radar chart because, although both are part of the technical dimension, they are calculated separately to elucidate all trade-offs more clearly.

These results suggest that the *Trade-off Value Protocol* provides a lens for noticing patterns in student design priorities and indicates varying levels of design competency. The representative student artifacts within Table 3 allow a glimpse into students' implicit decision-making.

The following subsections describe the five patterns of variation that emerged from the results of the Trade-off Value analysis: (A) balanced trade-offs, (B) maximized energy production, (C) maximized human dimension, (D) maximized energy production with minimized human dimension, and (E) minimized construction costs. Our goal in looking into these patterns of variation is to understand how the *Trade-off Value Protocol* does indeed capture design artifact quality that encompasses multiple complementary and competing dimensions and elaborate on its potential utility as a teaching and learning tool. The discussion includes design educator implications for each of the five patterns as the Trade-off Value creates a snapshot of students' implicit decision-making.

Table 3
Summary of five trade-off patterns.

Design artifact	Trade-off Value (out of 400)	Pattern description
<p><i>Case A: Balanced trade-offs</i></p> <p>Energy = -3,621 kWh (-2.45 kWh/m³) Cost = \$214,573 (\$145.47/m³) Total area = 245.8 m² Window-to-wall ratio = 0.3 Constraints met = 8/8 Approx. volume = 1,475 m³</p>	<p>Trade-off Value = 311/400</p>	<ul style="list-style-type: none"> • Attractive and livable • Energy-efficient • Cost-effective • Met all constraints
<p><i>Case B: Maximized energy production</i></p> <p>Energy = -3,900 kWh (-20.3 kWh/m³) Cost = \$150,248 (\$195.6/m³) Total area = 192 m² Window-to-wall ratio = 0.15 Constraints met = 8/8 Approx. volume = 768 m³</p>	<p>Trade-off Value = 241/400</p>	<ul style="list-style-type: none"> • Less attractive and livable • Expensive house (on volumetric basis) • Energy-efficient • Met all constraints
<p><i>Case C: Maximized human dimension</i></p> <p>Energy = +32,833 kWh (25.2 kWh/m³) Cost = \$277,847 (\$212.9/m³) Total area = 174 m² Window-to-wall ratio = 0.4 Constraints met = 8/8 Approx. volume = 1,305 m³</p>	<p>Trade-off Value = 198/400</p>	<ul style="list-style-type: none"> • Attractive and livable (huge windows) • Expensive house • Not energy-efficient • Met all constraints

Table 3
(Continued)

Design artifact	Trade-off Value (out of 400)	Pattern description
<p><i>Case D: Maximized energy while minimizing human dimension</i></p> <p>Energy = +270 kWh (0.75 kWh/m³) Cost = \$72,557 (\$201.5/m³) Total area = 80 m² Window-to-wall ratio = N/A Constraints met = 6/8 Approx. volume = 360 m³</p>	<p>Trade-off Value = 118/400</p>	<ul style="list-style-type: none"> • Not attractive or livable • Cost was moderate (on volumetric basis) • Energy-efficient • Met 6/8 constraints
<p><i>Case E: Minimized construction costs</i></p> <p>Energy = 4,003 kWh (31.8 kWh/m³) Cost = \$41,089 (\$326.1/m³) Total area = 28 m² Window-to-wall ratio = 0.2 Constraints met = 6/8 Approx. volume = 126 m³</p>	<p>Trade-off Value = 93/400</p>	<ul style="list-style-type: none"> • Not attractive, large windows • Expensive house (on volumetric basis) • Not energy-efficient • Met 6/8 constraints

Case A: Balanced Trade-Offs

This is a pattern of balanced trade-offs, which was demonstrated in 10% of the student sample, with Trade-off Values ranging from 246.05 to 310.84, and a median of 260.14. Overall, higher Trade-off Values appear to indicate a reasonable level of performance for each of the three design dimensions (economic, human, and technical) while also meeting all design constraints. Trade-offs are complex: while decreasing the window-to-wall ratio has a positive impact on overall construction costs and energy consumption, it has a negative impact on the livability of the home. An example of this pattern is shown in Figure 2, which demonstrates an effective solution in terms of performing at the top of the school. While no one design dimension was optimized, the result is a livable house that performs well against cost constraints and energy goals. The energy consumption is in the top 30% performance of each school, and window-to-wall ratio is in the top half.

This pattern of student artifacts reflects at least moderate performance among all three dimensions, with a slight push towards optimal performance in one dimension. This is a different pattern from the other remaining four patterns in that artifacts in this pattern encompass a more comprehensive system of performance, rather than optimization of one sole dimension with varying levels of attention to other dimensions. In focusing attention on making balanced trade-offs within their design solution, these students are progressing towards behaving as informed designers. Their design solutions include comprehensive coverage of the objectives, and no one priority is taking precedence.

Design educator implication: This group of students is already taking a systems approach to understanding design prompts by addressing multiple design dimensions, and is already exhibiting behaviors that instructors would want to see. To help nurture this type of student design expertise, an educator should prompt them to explain what they like best and least about this design to make them more aware of the trade-offs they have considered. In discussing these trade-offs, students are likely to make important science concept connections (Purzer et al., 2015).

Figure 2. Case A: balanced trade-offs. (a) Final artifact. (b) Trade-off value (311/400).

Case B: Maximized Energy Production

Students who follow this pattern focus on energy while still attending to the human dimension. This pattern was observed in 34% of the student sample, with Trade-off Values ranging from 115.17 to 274.49, and a median of 200.63. The design prompt explicitly directed students to minimize the energy needed in their solution. Students' energy consumption performed at the 80th percentile or higher, with energy production of at least 4,000 kWh. Analysis of the collective student sample suggests that some students focused mostly on the technical aspect of their design, which in this context meant minimizing the annual energy consumption. Figure 3 shows a representative design of a student who employed this strategy. The design artifact in question is a relatively simple form with few windows and a high number of solar panels, with a resulting quality score in the top quartile of the Trade-Off Values for the school.

Energy consumption appears to be the main focus, although the overall Trade-off Value is also in the top quartile for the school (top 100 of approximately 400 total students). This case achieved low energy consumption, yet the overall design quality suffered in total cost on a volumetric basis and the human dimension as demonstrated through the window-to-wall ratio. The case presented for this group shows that even when employing a design strategy of minimizing energy consumption, the overall performance of the home varied depending on the extent to which the students focused on the other dimensions of the project, as well as the degree of addressing design criteria and constraints. This group of students produced a design artifact that primarily emphasized the technical dimension at the expense of the human and economic dimensions. In focusing their attention on one aspect of their design, these students are behaving as beginning designers.

Design educator implication: This group of students tends to produce design artifacts that primarily emphasize the technical dimension, potentially at the expense of the human and economic dimensions. They may be artificially reducing design goals to be more manageable cognitively and thus reducing complexity to prioritize the technical, which can be tested quickly via the software. It is helpful to encourage these students to consider all dimensions involved in the design

Figure 3. Case B: maximized energy production. (a) Final artifact. (b) Trade-off value (241/400) components.

prompt, but also to affirm their optimization efforts, challenging them to keep technical performance high while also trying to reduce costs and improve aesthetics in their next iteration.

Case C: Maximized Human Dimension

Students who follow this pattern focus on the human dimension at the expense of the technical one. This pattern was observed in 23% of the student sample with Trade-off Values ranging from 110.08 to 276.65, and a median of 222.7. This third pattern illustrated by the *Trade-off Value Protocol* is maximizing aesthetics through large windows. This case (Figure 4) is a representative design of a student who employed this strategy. While investigating students in this group, they appear to focus on optimizing a particular feature (window-to-wall ratio) while still working within the design criteria and constraints, resulting in a moderate level of performance. This case represents a house that included large windows on each wall, and performed at the top of the school for the human dimension of the design. However, it appears that the large windows contribute to large energy consumption, as the annual energy consumption is one of the highest in the school (low percentile rank of 5.8). In addition, the volumetric construction cost of the house was high in relation to the rest of the school due to the large windows (low percentile rank of 16.67). The design solution met all required design criteria and constraints. In general, students in this group had solutions that ranked in the 80th percentile for the human dimension, but in the technical dimension ranged from the 1st percentile to the 78th percentile.

The student artifacts within this group show that attending to the aesthetics and livability of the design might come at the expense of the other design dimensions such as cost and energy. However, focusing on the aesthetics through the windows did not seem to distract from the ability to meet design criteria and constraints, helping the overall Trade-off Value. This group of students produced a design artifact that emphasized the human dimension, at the expense of the technical and economic dimensions. In focusing their attention on one aspect of their design, these students are behaving as beginning designers.

Design educator implication: This group of students tended to explore complicated shapes and configurations beyond a simple square or rectangle, but at the expense of economic and technical dimensions. These students should be encouraged to continue to understand a human user and to consider either decreasing costs or increasing energy efficiency in their next iteration to understand the interaction of two design criteria at a time.

Figure 4. Case C: maximized human dimension. (a) Final artifact. (b) Trade-off value (198/400) components.

Case D: Maximizing Energy Efficiency While Minimizing Human Dimension

Students who follow this pattern maximized energy production at the expense of both cost and the human dimension. This pattern was observed in 19% of the student sample. Trade-off Values ranged from 115.17 to 245.79, with median of 194.26 (the lowest median of all groups). The fourth pattern among Trade-off Values appeared to have an opposite focus to the third pattern in attending to the human dimension of design (see Figure 5). This case includes design artifacts that seem to neglect the livability of the design. Not featuring windows results in both a jarring appearance and failure to meet the constraint for a window on each wall. However, the lack of windows allowed this design solution to be quite energy efficient. This home had a relatively high energy score (energy consumption percentile rank of 87.25). Nonetheless, the overall Trade-off Value was in the lowest quartile of the school. This student failed to meet the window requirement of at least one window per wall, and the overall Trade-off Value reflects the lack of focus on design constraints. With respect to

Figure 5. Case D: maximizing energy while minimizing human dimension. (a) Final artifact. (b) Trade-off value (118/400) components.

the human dimension, solutions in this group's scores ranged from the 1st to 39th percentile, while the technical dimension was at least at the 81st percentile.

The pattern of neglecting particular features of the house (i.e., no windows), combined with not meeting all design criteria and constraints, results in poor performance relative to the whole school. This group of students produced a design artifact that seemed to ignore the human dimension (livability) and the economic dimension. The performance in energy consumption seems to suggest that the technical dimension was a key focus. In focusing their attention on one aspect of their design, while also not considering a user, these students are behaving as beginning designers.

Design educator implication: This group of students tends to focus on optimizing an element of the design artifact such as cost or a technical aspect at the expense of human-centered design. Design educators should encourage the students in this group to take a step back and consider who would want to live in that house, and what they can do to improve the livability and desirability of their design.

Case E: Minimized Construction Costs

Students who follow this pattern minimized construction costs. This pattern was observed among 14% of the student sample, with Trade-off Values ranging from 103.19 to 256.76 and median of 208.29. The design prompt explicitly directed students to minimize construction cost of their home, with a limit of \$250,000 (see Table 1). Some students appeared to use this guidance as a goal to design as inexpensive a home as possible. A representative design solution of a student who employed this strategy is shown in Figure 6. Despite minimal overall construction cost, the footprint of the home was quite small, so the cost per volume was not as effective in producing a livable space. As a result, this design artifact performed in the lowest quartile for that school (percentile rank of 3.92). The window-to-wall ratio was very competitive, in the top quarter of the designs, but that was due to the small scale of the house. In addition, the lack of solar panels contributed to a

Figure 6. Case E: minimized construction costs. (a) Final artifact. (b) Trade-off value (93/400) components.

low cost at the expense of not reducing energy consumption. Notably, the artifact did not meet all of the technical constraints by failing to (1) design a home large enough for a family of four and (2) include at least one window on each side of the house.

For other student solutions that took a similar approach, the strategy of minimizing cost often had a big impact on the overall quality of the design, as this design strategy was also linked with not meeting all of the design constraints. Because these homes were smaller than the others within their school, on a volumetric cost basis they were not as effective. This group of students produced a design artifact that primarily emphasized the economic dimension at the expense of the human and technical dimensions. In focusing their attention on one aspect of their design, these students are behaving as beginning designers.

Design educator implication: This group of students tends to produce a design artifact that primarily emphasizes the economic dimension at the expense of human and technical dimensions. It is helpful to encourage the students to consider all dimensions involved in the design prompt, but to also affirm their optimization efforts in costs. Challenge them to keep costs low while also trying to lower energy consumption costs or increasing the livability and aesthetics of the design artifact in their next iteration. It is also important to help this group of students see that they have not addressed design criteria and constraints (such as having one window per wall and a minimum required size) as design criteria and constraints are an important part of engineering and design practice.

Trade-off Value Protocol: Can Be Applied Consistently and Systematically

The *Trade-off Value Protocol* can be applied consistently in many scenarios because it is a function of setting quantitative parameters (i.e., across technical and economic dimensions). The Trade-off Value is quantified as a performance outcome, and is thus measurable. The overall score and each dimensional sub-score are not subject to interpretation in rating or judging. However, how each dimension is included as a metric may be subjective, if it is then applied consistently and systematically. For example, the *Trade-off Value Protocol* can be applied to a subjective idea such as livability but allows a clear and consistent measurement rubric for this subjective idea.

The *Trade-off Value Protocol* is also relatively easy to use. As a first step, the design educator needs to set parameters to measure within human, technical, and economic dimensions. Then, the design educator needs to clarify if a goal is to maximize or minimize that dimension. A next step is to set measures of the dimension and perform any needed calculations (e.g., window-to-wall ratio as surrogate of livability). While measuring dimensions in design platforms such as Energy3D is clear, creating and measuring dimensions in other design environments may be more ambiguous and may be more labor-intensive. Finally, the design educator will compute the percentile ranks of each dimension, summing the individual dimension ranks for the total Trade-off Value.

The composite score of the Trade-off Value can illuminate the extremes of student work, because it helps distinguish students who make design trade-offs well from those who ignore them. Understanding students with middling Trade-off Values for a sample or school would require a deeper look into each of the separate measures. Therefore, the Trade-off Value is a launching point for educators to understand quickly how students are developing as designers with respect to making trade-off decisions. The composite score shown in Equation 1 first requires calculating the percentile ranks of each dimension, which can be calculated succinctly in common software such as Excel. Next, all of the percentile ranks are added together. While the composite score could have been calculated in more sophisticated mathematical representations, such as logistic functions, the utility of the *Trade-off Value Protocol* is ease of use for educators.

Trade-off Value Protocol: Indicates Design Competency

Four of the five patterns of design artifacts discussed earlier and summarized in Table 3 resemble what we would expect among beginning designers with respect to making trade-offs. In Cases B–E, students tended to focus on just one dimension at the expense of at least one other dimension. Alternatively, in Case A, the pattern of balanced trade-offs, the students tended to take a holistic approach to focusing on all dimensions of the design task. For the entire sample of students who demonstrated this pattern of balanced trade-offs, no one criterion ranked below the 56th percentile in this group, suggesting trade-offs require at least a moderate performance on all criteria. While informed designers are skilled at weighing the pros and cons of a design (Crismond & Adams, 2012), beginning designers have not yet fully developed that skill. Instead, they tend to focus only on one aspect (i.e., pro or con) of a design (Crismond & Adams, 2012). In this study, the tendency to focus only on one aspect is evidenced by the fact that the majority of students ended up with a high score in one dimension but a lower and problematic score in other dimensions. Cases B, C, and E (the patterns of optimizing energy consumption, maximizing aesthetics through large windows, and minimizing construction costs, respectively) speak to a beginning designer's tendency to focus on only one feature of a design at once. Beginning designers are often "oblivious" to the

complex trade-offs involved in a particular design (Crismond & Adams, 2012). Case D, the pattern of maximizing energy while minimizing the human dimension, is an even more exaggerated instance of focusing on one feature. Students in Case D exhibited a similar singular focus while ignoring or intentionally excluding human comfort considerations. Case A differs from the other cases in that students in Case A appear to be moving towards informed design practices by taking a more comprehensive approach to weighing the complex dimensions in a design challenge. Case A is exemplified by overall high performance within each of the four dimensions and holistically through a high composite Trade-off Value. In addition, looking across the sub-scales of the Trade-off Value (human, technical, and economic) shows that no one area was neglected.

The *Trade-off Value Protocol* allows design educators to understand how students address trade-off dimensions in producing design artifacts. The overall score gives a glimpse into the degree to which all dimensions were adequately addressed, distinguishing groups of students who attend to the complexity of design factors well. In this study, a noticeable proportion of students with limited experience in design practice consider multiple dimensions with a predominant focus on a subset of technical, human, and economic dimensions. A smaller proportion of these students considers competing dimensions through either a balanced approach to making trade-offs or through an approach that follows a main focus while not completely neglecting other dimensions. In brief, this study features designers with limited experience, a minority of whom demonstrate balanced focus but with most exhibiting patterns of narrow focus.

Looking across the individual sub-scores that reflect performance within each of the dimensions provides a way to understand the focus of a particular student's design. For example, a sub-score of high performance in the technical dimension (energy) but low performance in the human (livability) and economic (cost) dimensions would suggest that this student is making trade-offs like a beginning designer. Conversely, a high composite Trade-off Value and attention to Trade-off Value sub-scales might indicate a developing competency in design, particularly with respect to design decisions. The *Trade-off Value Protocol* could thus be a powerful tool for students to make visible their design priorities, and for design educators to help scaffold more meaningful design iterations. Moreover, the *Trade-off Value Protocol* might serve as a helpful tool to encourage other important design behaviors such as iteration.

Limitations

While the *Trade-off Value Protocol* of assessing design artifact quality offers affordances over current methodological approaches and tools, there are some limitations. To begin with, this analysis was conducted in the context of a design challenge that asked students to consider multiple criteria rather than optimizing one feature. While the design challenge asked students to address energy, cost, and aesthetics, the design solution that they deemed best may not have had the highest trade-off value. The *Trade-off Value Protocol* in its current form assigns equal weighting of importance among all design dimensions. However, the equation could be modified to account for assigning different weights to different design priorities (i.e., if driving energy consumption as low as possible were twice as important as maintaining a low cost). A second feature of the *Trade-off Value Protocol* involves using percentile rank, which makes the evaluation group-dependent. For instance, a particular student's Trade-off Value could be quite different in a classroom of students who are skilled at balancing multiple criteria as compared to a classroom focused more on one criterion such as cost or energy. Therefore, special consideration is required before looking across multiple schools or samples to produce a design quality score for research purposes. Relatedly, this calculation method requires the same design task to be completed or a design project with easily comparable performance criteria, because percentile-based performance requires a similar scale for comparisons across designs. Future work should investigate how the *Trade-off Value Protocol* for assessment compares to other holistic, norm-referenced assessment techniques, such as adaptive comparative judgment, which can incorporate peer evaluation in formative or summative use to judge and rank peers' work (Bartholomew & Strimel, 2017; Bartholomew et al., 2018; Pollitt, 2012; Strimel et al., 2020).

Most importantly, this equation still requires judgment and thought. The ability to customize the equation to criteria is a strength of the *Trade-off Value Protocol* as it makes the calculation adaptable. However, it also creates a need to consider the goal and how the individual criteria fit this goal. Once that judgement of criteria is made, the *Protocol* can be applied consistently. For example, adding an extra design criterion in the human dimension would make that human portion more heavily weighted than the other components. As such, an average of the percentile ranks of the human dimension might be a more appropriate measure. This study also tested the *Trade-off Value Protocol* in the context of a design task in Energy3D, which allows clear quantification of performance in areas such as cost and energy consumption. The Trade-off Value is certainly not limited to this context, but it will require exploration into ways that competing dimensions can be quantified. We can imagine that dimensions such as cost and technology might lend themselves better to quantitative measures, but the human dimension might be more obscure. Within this design challenge, we quantified the human criteria as a window-to-wall ratio. The human dimension is a key feature of design, and therefore should not be ignored in the pre-college

classroom. However, quantifying qualitative criteria may range in difficulty between different design challenges and could encompass a wide range of human factors such as safety, comfort, aesthetics, convenience, quality, and usability, among others.

Conclusions and Teaching Implications

Previous research asserts that people in general struggle to evaluate trade-offs between two attributes of very unequal importance where the option should be “obvious” (Scholten & Sherman, 2006). Studies conducted with college students suggest students do not fully characterize their design decisions and do not reliably understand how to manage conflicting criteria (Girod et al., 2003; Younker & McKenna, 2009). Since studies show people do not make trade-off decisions easily or well, we have developed a pedagogical tool to help teach and support better decision-making.

Our research aimed to understand the variations in how beginning design students approach trade-offs through their design artifacts. In particular, results from this study suggest that beginning designers exhibit varying patterns of making trade-offs. Some students are able to produce design artifacts that demonstrate an attention to managing competing and complementary design criteria such as cost, energy efficiency, and livability. This finding bolsters research from Purzer et al.’s (2013) work with grade school students, which implied that young students can make trade-offs between cost and effectiveness. The results that highlight variation in the ways students make design trade-off decisions confirm the need for meaningful assessment of student design artifacts.

In assessing design artifacts, there is a need for models that “strive to more clearly identify the sets used, the discriminating objectives considered and the measurement systems” to facilitate “better communication, understanding, and results” (Otto, 1995, p. 100). The *Trade-off Value Protocol* is a useful method to communicate overall effectiveness, and it addresses a void in other designer and research measurement methodologies in three areas. First, because it is conceptually grounded in the idea of design trade-offs (i.e., meeting multiple and competing performance goals), it provides a comprehensive way to think about the interaction of client/user priorities, design possibilities, and objective measures. Second, the *Protocol* is easy to use. Third, the *Trade-off Value Protocol* represents an important feature of design competency with which beginning designers struggle—making design trade-off decisions.

The *Trade-off Value Protocol* could be a useful tool for students, educators, and researchers. It is important to furnish pre-engineering students with an awareness of the inherent trade-offs involved in engineering design, because it is an essential part of the practice of engineering. These studies have great implications for design educators in college and pre-college settings. A major utility is helping make design decisions explicit in a visual sense, as seen in Table 3. The overall Trade-off Value and sub-scales could help students see shortcomings in their designs by making visible the attributes they were ignoring at the expense of optimizing something else. A second benefit of the *Trade-off Value Protocol* is in scaffolding reflective thinking. Pairing the *Protocol* with a discussion of design artifact performance as a whole, as well as along each dimension, with a reflection on the pros and cons of the designs might help students understand the strengths and weaknesses of their artifacts and could lead to an informed process of iteration and improvement.

This study also has important implications for design researchers. First, the *Trade-off Value Protocol* offers a useful way to measure design quality that encompasses multiple complementary and competing dimensions. As such, it has great potential utility in studying the relationships between design artifact quality and various design behaviors and cognition. Moreover, because the *Trade-off Value Protocol* is relatively easy to use and can be applied systematically, it can be scaled up for studies of larger numbers of students to investigate more generalizable patterns.

In future research, we will continue to test the *Trade-off Value Protocol* in similar design challenges with different types of students (e.g., different ages of pre-engineering and engineering students, different types of schools, etc.) and experiment with design challenges outside of the Energy3D platform to comprehend more fully the general utility of the *Trade-off Value Protocol* and the degree of generalizability of the five patterns of trade-offs illuminated in this study. Finally, this study focused on trade-offs as evidenced from student design artifacts and “[A]lthough a solution is desired at the conclusion of an engineering design challenge, the process the students take is also important” (Lammi et al., 2018, p. 54). Future work will use the *Trade-Off Value Protocol*, together with conceptual knowledge and student decision justification, to understand further how students make design trade-off decisions.

Acknowledgments

This work would not have been possible without the collaboration of the Creekside Middle School instructional coach, Bob Loy, and science and mathematics teachers (Chris Bartley, Jeff Kirch, Becky Cheetham, Katie Abel, Joel Haynie, and Madison Schaffer), Jeannette Melcic at Hammond Middle School, and their creative students. We also would like to express our gratitude to the Concord Consortium for their innovative software and support, especially Charles Xie, Jie Chao, and

Saeid Nourian as well as Corey Schimpf at the University at Buffalo. We thank our reviewers whose feedback pushed our thinking and served to improve our final manuscript. The work presented in this paper is based upon work supported by the National Science Foundation (NSF) under Grant DUE #1348547 and DUE #1348530 as well as the Bilsland Dissertation Fellowship given by the Purdue University Graduate School. Any opinions, findings, and conclusions or recommendations expressed in this paper, however, are those of the authors and do not necessarily reflect the views of the NSF.

Author Bios

Molly H. Goldstein is a Teaching Assistant Professor in the College of Engineering at the University of Illinois. Her research focuses on design learning along the K-16 continuum, with a specific emphasis on design decision-making and engineering judgement. Email: mhg3@illinois.edu, Website: <https://mollygoldstein.ise.illinois.edu>

Robin S. Adams is a Professor in the School of Engineering Education at Purdue University. She is a national leader in researching interdisciplinary thinking and design learning, in connecting research and practice, and in building research capacity in engineering education. Email: rsadams@purdue.edu

Senay Purzer is a Professor in the School of Engineering Education at Purdue University and the Director of Assessment Research at the INSPIRE Institute for Pre-college Engineering Research. Her research focuses on design learning and assessment in complex design learning environments with a specific focus on student decision-making and innovation processes. Email: purzer@purdue.edu

References

- Accreditation Board for Engineering and Technology. (2019). *Criteria for accrediting engineering programs, 2019–2020*. <https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/>
- Akin, Ö., & Lin, C. (1996). Design protocol data and novel design decisions. In *Analysing design activity* (Vol. 16, pp. 35–63). [http://dx.doi.org/10.1016/0142-694X\(94\)00010-B](http://dx.doi.org/10.1016/0142-694X(94)00010-B)
- Asimow, M. (1962). *Introduction to design*. Englewood Cliffs, NJ: Prentice-Hall.
- Asunda, P. A., & Hill, R. B. (2007). Critical features of engineering design in technology education. *Journal of Industrial Teacher Education*, 44(1), 25–48. <http://scholar.lib.vt.edu/ejournals/JITE/v44n1/asunda.html>
- Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education*, 96(4), 359–379. <https://doi.org/10.1002/j.2168-9830.2007.tb00945.x>
- Atman, C. J., Cardella, M. E., Turns, J., & Adams, R. (2005). Comparing freshman and senior engineering design processes: An in-depth follow-up study. *Design Studies*, 26(4), 325–357. <https://doi.org/10.1016/j.destud.2004.09.005>
- Atman, C. J., Kilgore, D., & McKenna, A. (2008). Characterizing design learning: A mixed-methods study of engineering designers' use of language. *Journal of Engineering Education*, 97(3), 309–326. <https://doi.org/10.1002/j.2168-9830.2008.tb00981.x>
- Bartholomew, S. R., & Strimel, G. J. (2017). Adaptive comparative judgment: A better way of assessment. *Techniques*, 92(3), 44–49.
- Bartholomew, S. R., Strimel, G. J., & Jackson, A. (2018). A comparison of traditional and adaptive comparative judgment assessment techniques for freshman engineering design projects. *International Journal of Engineering Education*, 34(1), 20–33.
- Brockman, J. (2009). *Introduction to engineering: Modeling and problem solving*. John Wiley & Sons.
- Brown, T. (2009). *Change by design: How design thinking transforms organizations and inspires innovation*. New York: HarperCollins.
- Cardella, M. E., Atman, C. J., Turns, J., & Adams, R. S. (2008). Students with differing design processes as freshmen: Case studies on change. *International Journal of Engineering Education*, 24(2), 246–259.
- Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, 101(4), 738–797. <https://doi.org/10.1002/j.2168-9830.2012.tb01127.x>
- Cross, N. (2008). *Engineering design methods: Strategies for product design* (4th ed.). John Wiley & Sons. [https://doi.org/10.1016/0261-3069\(89\)90020-4](https://doi.org/10.1016/0261-3069(89)90020-4)
- Demirel, H. O., & Duffy, V. G. (2017). Incorporating tactile cues into human-centered virtual product design. *Human Factors and Ergonomics in Manufacturing*, 27(1), 5–16. <https://doi.org/10.1002/hfm.20402>
- Dieter, G., & Schmidt, L. (2009). *Engineering design* (4th ed.). New York, NY: McGraw-Hill.
- Dong, A., Hill, A. W., & Agogino, A. M. (2004). A document analysis method for characterizing design team performance. *Journal of Mechanical Design*, 126(3), 378. <https://doi.org/10.1115/1.1711818>
- Dorst, K. (2006). Design problems and design paradoxes. *Design Issues*, 22(3), 4–17. <https://doi.org/10.1162/desi.2006.22.3.4>
- Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, 94(1), 103–120. <https://doi.org/10.1002/j.2168-9830.2005.tb00832.x>
- Dym, C. L., Little, P., Orwin, E. J., & Spjut, E. (2009). *Engineering design: A project-based introduction* (3rd ed.). John Wiley & Sons.
- Gabbay, D. M., Thagard, P., Woods, J., & Meijers, A. (2009). *Philosophy of technology and engineering sciences*. North Holland.
- Gann, D., Salter, A., & Whyte, J. (2003). Design quality indicator as a tool for thinking. *Building Research & Information*, 31(5), 318–333. <https://doi.org/10.1080/0961321032000107564>
- Girod, M., Elliott, A. C., Burns, N. D., & Wright, I. C. (2003). Decision making in conceptual engineering design: an empirical investigation. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 217(9), 1215–1228.
- Goel, V., & Pirolli, P. (1992). The structure of design problem spaces. *Cognitive Science*, 16(3), 395–429. [https://doi.org/10.1016/0364-0213\(92\)90038-V](https://doi.org/10.1016/0364-0213(92)90038-V)
- Goldstein, M. H., Adams, R. S., & Purzer, S. (2020, October). Examining approaches to measuring trade-offs in design artifacts. *Proceedings from the IEEE Frontiers in Education (FIE) Annual Conference*, Uppsala, Sweden. <https://doi.org/10.1109/FIE44824.2020.9274261>

- Goldstein, M. H., Vieria, C., Adams, R. S., Purzer, S., & Zielinski, M. K. (2016, October). Developing a measure of quality for engineering design artifacts. *Proceedings of the IEEE Frontiers in Education (FIE) Annual Conference*, Erie, PA. <https://doi.org/10.1109/FIE.2016.7757346>
- Hay, L., Duffy, A. H. B., McTeague, C., Pidgeon, L. M., Vuletic, T., & Greal, M. (2017). A systematic review of protocol studies on conceptual design cognition: Design as search and exploration. *Design Science*, 3, e10. <https://doi.org/10.1017/dsj.2017.11>
- International Technology Education Association. (2000). *Standards for technology literacy*. Reston, VA.
- Jonassen, D., Strobel, J., & Lee, C. (2006). Everyday problem solving in engineering: Lessons for engineering educators. *Journal of Engineering Education*, 95(2), 139–151. <https://doi.org/10.1002/j.2168-9830.2006.tb00885.x>
- Lammi, M., Denson, C., & Asunda, P. (2018). Search and review of the literature on engineering design challenges in secondary school settings. *Journal of Pre-College Engineering Education Research*, 8(2), 49–66. <https://doi.org/10.7771/2157-9288.1172>
- Lan, L., Kannan, P. K., & Ratchford, B. T. (2008). Incorporating subjective characteristics in product design and evaluations. *Journal of Marketing Research*, 45(2), 182–194. <https://doi.org/10.1509/jmkr.45.2.182>
- Miles, M. B., & Huberman, A. M. (1994). *Qualitative Data Analysis: An Expanded Sourcebook*. Thousand Oaks, CA: Sage Publications.
- Monteagut, L. E. (2017). Etic approach to qualitative research. *International encyclopedia of communication research methods*. Wiley. <https://doi.org/10.1002/9781118901731.iecrm0092>
- National Academy of Engineering and the National Research Council. (2009). *K-12 engineering education: Understanding the status and improving prospect*. Washington, DC: National Academies Press.
- National Academy of Engineering and the National Research Council. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. Washington, DC: National Academies Press.
- National Research Council. (2011). *Successful K-12 STEM education: Identifying effective approaches in science, technology, engineering, and mathematics*. Washington, DC: National Academies Press.
- National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press. <https://doi.org/10.17226/13165>
- NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. Washington, DC: The National Academies Press. <http://www.nextgenscience.org/>
- Niku, S. (2009). *Creative design of products and systems*. John Wiley & Sons.
- Oakes, W., Leone, L., & Gunn, C. (2006). *Engineering your future: A comprehensive introduction to engineering* (5th ed.). Wildwood, MO: Great Lakes Press.
- Otto, K. N. (1995). Measurement methods for product evaluation. *Research in Engineering Design*, 7(2), 86–101. <https://doi.org/10.1007/BF01606904>
- Pollitt, A. (2012). The method of adaptive comparative judgement. *Assessment in Education: Principles, Policy & Practice*, 19(3), 281–300. <https://doi.org/10.1080/0969594X.2012.665354>
- Privitera, G. (2015). *Statistics for the behavioral sciences* (2nd ed.). Newbury Park, CA: SAGE Publications.
- Pugh, S. (1990). *Total design: Integrated methods for successful product engineering*. Boston, MA: Addison-Wesley. <https://doi.org/10.1049/ir:19920033>
- Purzer, S., & Chen, J. (2010, June). Teaching decision making in engineering: A review of textbooks and teaching approaches. *Proceedings from the American Society for Engineering Education Annual Conference & Exposition*, Louisville, KY. <https://doi.org/10.18260/1-2--15942>
- Purzer, S., Duncan-Wiles, D., & Strobel, J. (2013). Cost or quality? Teaching fourth and fifth graders about engineering optimization and trade-offs. *Science and Children*, 50(5), 34.
- Purzer, S., Goldstein, M. H., Adams, R. S., Xie, C., & Nourian, S. (2015). An exploratory study of informed engineering design behaviors associated with scientific explanations. *International Journal of STEM Education*, 2(1), 9. <https://doi.org/10.1186/s40594-015-0019-7>
- Scholten, M., & Sherman, S. J. (2006). Tradeoffs and theory: The double-mediation model. *Journal of Experimental Psychology: General*, 135(2), 237.
- Strimel, G. J., Bartholomew, S. R., Purzer, S., Zhang, L., & Ruesch, E. Y. (2020). Informing engineering design through adaptive comparative judgment. *European Journal of Engineering Education*, 1–20. <https://doi.org/10.1080/03043797.2020.1718614>
- Strobel, J., & Pan, R. (2010). Compound problem solving: Insights from the workplace for engineering education. *Journal of Professional Issues in Engineering Education & Practice*, 137(4), 215–222. [https://doi.org/10.1061/\(ASCE\)EI.1943-5541.0000047](https://doi.org/10.1061/(ASCE)EI.1943-5541.0000047)
- Thurston, D. L. (1991). A formal method for subjective design evaluation with multiple attributes. *Research in Engineering Design*, 3(2), 105–122. <https://doi.org/10.1007/BF01581343>
- Xie, C., Schimpf, C., Chao, J., Nourian, S., & Massicotte, J. (2018). Learning and teaching engineering design through modeling and simulation on a CAD platform. *Computer Applications in Engineering Education*, 26, 1–17. <https://doi.org/10.1002/cae.21920>
- Yang, M. C. (2003). Concept generation and sketching: Correlations with design outcome. *ASME 2003 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 829–834). <https://doi.org/10.1115/DETC2003/DTM-48677>
- Yang, M. C. (2005). A study of prototypes, design activity, and design outcome. *Design Studies*, 26(6), 649–669. <https://doi.org/10.1016/j.destud.2005.04.005>
- Yang, M. C. (2009). Observations on concept generation and sketching in engineering design. *Research in Engineering Design*, 20(1), 1–11. <https://doi.org/10.1007/s00163-008-0055-0>
- Younker, J., & McKenna, A. (2009). Examining student use of evidence to support design decisions. *Proceedings from the American Society for Engineering Education Annual Conference*, Austin, TX. <https://doi.org/10.18260/1-2--4921>