

Investigating Middle-School Students' Conceptions of Trade-offs in Design*

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The recent reform efforts in K-12 education urge for the integration of engineering with other subject matter such as science. Design, a core practice in engineering, is new to many K-12 students, and thus, little is known about their design strategies and conceptions. One design strategy, making trade-offs, is a necessary design practice, and is a key performance dimension in student design. However, research on K-12 students' conceptions of balancing trade-offs is limited. Such research is essential as we attempt to understand how students become informed designers and how we can support their transformation. Understanding how students prioritize design strategies after taking part in a design activity allows an opportunity to see how students' conceptions of design activities change. In particular, this multi-method work addresses students' use and prioritization of the term "balancing trade-offs" in design through the following research questions: (1) Do students report changes in their perceived importance of "balancing trade-offs" after engaging in a design project, and (2) How students' *conceptions* of "balancing trade-offs" change after introduction of a design activity. This survey was administered as a pre- and post-test assessment in three middle schools with over 700 students. We performed McNemar tests to quantitatively understand changing conceptions and qualitatively analyzed open-responses to get a deeper understanding of students' rationale. Results suggest that after a design activity, "balancing trade-offs" became a statistically more important concept to students, but that students still did not have a sophisticated understanding of the term without dedicated instruction.

Keywords: engineering design; K-12; trade-offs; design decisions

1. Introduction

Design and decision-making are intertwined for practicing engineers. Trade-offs are a complex element of a decision, as the decision-maker weighs possible outcomes against their respective costs in areas such as budget, degree of safety, and various performance indicators [1]. Making trade-off decisions is a necessary design practice of informed designers, and is a key performance dimension that students may achieve in a K-16 design setting [2]. Understanding how students characterize their design trade-offs would allow educators a better glimpse into students' design thinking. Without such knowledge at the K-16 level, we cannot create suitable design activities for students to improve on their decision-making skills. These decision-making skills are critical not only for those students who pursue engineering, but also in general for problem solving skills and contribution to society.

While trade-offs in design are difficult, primary and secondary school children are found to be

capable of making trade-offs in design in previous research. For example, Purzer and colleagues examined elementary students evaluating designs by weighing cost and effectiveness [3]. Similarly, a separate study by Purzer et al., showed high school students were found to make science connections while taking part in an engineering design project while making trade-offs such as energy performance in different seasons [4]. In a 2011 study, Svarovsky found that middle school girls were able to develop engineering epistemology in the form of ruling out a design due to cost and evaluating trade-offs when making a decision [5]. Another study in middle school showed students provided justifications for trade-offs when optimizing a socioscientific design task [6]. All of these studies of K-12 students and their understanding of trade-offs involve small sample sizes. We argue that students' conceptions of key design practices can be determined by asking them to prioritize these practices and explain their reasoning in their prioritization.

Understanding how students value design strate-

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gies after taking part in a design activity allows an opportunity to see how students' conceptions of design change. In particular, this work addresses how students prioritize of the term "balancing trade-offs" in design. To accomplish this, we will address the following research questions:

RQ1. Do students report changes in their perceived importance of "balancing trade-offs" after engaging in a design project?

RQ2. If so, how do students' *conceptions* of "balancing trade-offs" change?

2. Literature review

2.1 Engineering design

Design is a distinguishing activity of engineering [8, 9]. Dym, et al. define design within an engineering context to mean, "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" [8, p. 104]. Bucciarelli explains that engineering design is a "social process of negotiation, or iteration, of rectifying missteps, even misconceptions—a process rich with ambiguity and uncertainty" [9, p. 7]. He notes the distinction between "knowing that" or conceptual and structural knowledge and "knowing how" or procedural knowledge for engineers. Decision-making sits in the middle of these two types of knowing as engineers require a combination of conceptual and procedural knowledge to make difficult design decisions. An example of this intersection can be seen in the design of an aircraft where conceptual knowledge of aerodynamics, propulsion, and controls (knowing that) must be coupled with understand how to apply these concepts learned in order to address a design need (knowing how).

2.2 Trade-offs in engineering design

Trade-offs are a complex element of an engineering design decision, as the decision-maker weighs possible outcomes against their respective costs [1]. A design process where designers can examine trade-offs and develop alternatives is likely to lead to a higher quality design. The National Research Council [10] in their report, *Theoretical Foundations for Decision Making in Engineering Design*, claim that the most critical and most impactful decisions are more likely to involve complicated trade-offs. They further clarify trade-offs in a design context as:

"These trade-offs are also subject to many uncertainties regarding customer buying preferences, user abilities and preferences, technology maturity and availability,

and competitive advantages of possible functions and features. These trade-offs usually cut across disciplinary boundaries in terms of balancing weight, power, speed, cost, and economy of use" [10, p. 10].

Engineering decision trade-offs can include elements such as risk, preference, quality, and reliability in multi-attribute, multi-stakeholder design contexts. Current engineering design trade-off research has prescriptively approached these difficult decisions. For example, Thurston [11] presents a scenario in the automotive industry where design engineers are considering trade-offs between environmental impact, manufacturing cost, and mechanical performance in order to design a more comprehensively competitive product. Quirante, Sebastian & Ledoux [12] discuss a trade-off analysis in truss design between overall performance of the structure through minimization of weight, mechanical strength of the member and design variability. Other examples include design of gearboxes where designers must consider trade-offs between performance, adaptability, and production costs [13].

While a strand of research attempts to prescribe the ways in which designers should make trade-offs, other research is more concerned with describing how designers make such trade-offs when actually designing. One such synthesis study, by Crismond & Adams [2], discusses "weigh options and make decisions" as one of the nine critical practices of informed designers. In particular the behavior of "weigh options and make decisions" is a distinguishing area for competent designers in terms of decision-making skill. Crismond and Adams discuss informed designers' ability to understand benefits and trade-offs when making decisions and their ability to justify these decisions. Informed engineering designers are skilled at "weighing and articulating" [2, p. 761] both the pros and cons of a particular design, and can look for trade-offs in even the best ideas. In contrast, beginning designers may have a tendency to ignore or give little attention to "the unavoidable tensions and trade-offs associated with design" [2, p. 761]. This stark difference between beginning and informed designers' trade-off behaviors suggests that their perceived importance of trade-offs also differs.

Studying engineers in the workplace has indicated the importance of making trade-offs for these engineers. In one such study, Jonassen, Strobel, & Lee [14], highlighted the importance of balancing competing needs and criteria as one of the attributes that differentiate workplace problems from class problems. In another investigation, Strobel & Pan [15], examined engineering workplace problems with results showing engineers weighing options and forecasting the impact of decisions on a wide variety of variables. The result of reviewing the

literature in trade-off decisions in engineering design is that informed designers and engineers in the workplace make trade-off decisions as an important part of their work. In the Conceptual Framework section, we discuss Asimow's [16] definition of design, which highlights the technical, human, and economic factors that engineers balance in their trade-off decisions.

2.3 Engineering design in undergraduate and K-12 education

Because design is so critical to the engineering profession, it is a core focus in engineering education at the college level [17]. In the United States, design has been explicitly recognized as a crucial component of an engineering education through accreditation criteria [18]. ABET states in Criterion 5 that "Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs" [18].

In 2012, the National Academies published a notable report, *A Framework for K-12 Science Education*, suggesting that K-12 education should integrate engineering with science education [19]. Followed by this report was the Next Generation Science Standards (NGSS) [20]. In the *Framework* as well as NGSS, engineering design is described as a core disciplinary practice as well as a disciplinary core idea. The *Framework* defines the role of trade-offs as part of the *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." [19, p. 209]

Because of the focus on engineering as a crucial part of science education through *A Framework* and NGSS, it is reasonable to assume that design will

become an educational focus for increasingly younger students in the near future. Coherent decision-making at the K-12 level is a component of problem solving abilities. Broadly enhancing problem solving abilities through engineering design with younger students has implications for the future of a robust STEM workforce. Moreover, an understanding of design thinking and behaviors in pre-engineering students would result in a better design education for these students and could allow more targeted education for university engineering students.

3. Conceptual framework

The conceptual framework for this study is based on Asimow's [16] characterization of balancing trade-offs as the interaction among competing factors to achieve high-quality designs. As shown in Fig. 1, this involves a "synthesis of technical, human, and economic factors; and it requires the consideration of social, political, and other factors whenever they are relevant" [16, p. 2].

Here, human refers to more than ergonomics by encompassing what humans want. Technical factor refers to design performance, often achieved through science and math concepts. Economic factor refers to monetary costs. Using a conceptual framework of trade-offs in design, [16] that characterizes the interaction between competing design factors, this study offers a theory about how high quality designs are developed. In doing so, this study also offers tools for understanding how to evaluate the quality of a design solution through a trade-off value. A design with a high trade-off value takes a systems approach to design, allowing consideration paid to the competing factors rather than focusing solely on optimizing one or two of the factors. This idea complements more current views such the IDEO model of human-centered design emphasizing the intersection of desirability, feasibility, and viability [21] for innovation.

4. Methods

This paper addresses how students use and prioritize the term "balancing trade-offs" in design through the following research questions: (1) How

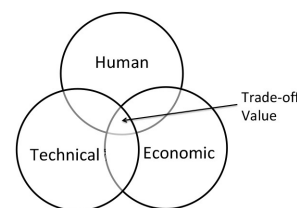


Fig. 1. Trade-off value conceptual framework.

do students' perceived importance of "balancing trade-offs" change after introduction of a design activity, and (2) How do students' *conceptions* of "balancing trade-offs" change after introduction of a design activity.

Previous design research with secondary students found that opportunities for meaningful science learning through engineering design occur when students attempt to balance benefits and trade-offs [4]. Based on this research and previous research with the Conceptions of Design Test (CDT) [22], we are assuming that (1) asking students to prioritize design practices based on importance allows us to get to an understanding of their notions of design, and (2) that young adults can explain their rationale in writing. While other methods such as student interviews and think aloud protocols would allow a more nuanced perspective on students' understanding of design language, these approaches constraint the study sample. With the use of the CDT, our goal is pragmatic with the aim to understand design conceptions of middle school population students.

4.1 Participants & design challenge

This research took place in three separate middle schools, with over 800 students ages 12–14 in the Midwest United States. One of the schools is located in a resource-challenged, urban area where the vast majority of students qualify for free or reduced lunch. The two other schools are located in a resource-rich school district in a suburban setting. However, this study does not aim to compare outcomes in these populations; rather, drawing data from students from a diverse array of backgrounds will allow variation of data as well as generalizability of our results. The students participated in an in-class design project using Energy3D (<http://energy.concord.org/energy3d/>), a CAD simulation environment. Energy3D is developed by the Concord Consortium as "a computer-aided engineering tool for designing, analyzing, and constructing green buildings and power stations that utilize renewable energy" [23]. The user-friendly software offers a simple 3D graphical user interface for drawing buildings, and evaluating their performance using cost and energy (solar and heat) simulations (see Fig. 2a–b).

Students were asked to design an energy-efficient home with the goal of consuming net-zero energy, while still maintaining an attractive, inhabitable, and comfortable design at a reasonable construction costs. While each student used the Energy3D design environment, the implementation of the design project varied in time and scale. Two of the schools used about two weeks of in-class time while the third school used four weeks and integrated the project across more than one subject area. Despite

the differences in implementation scale, none of the design activities across the three schools provided explicit instruction regarding trade-offs or other design terms. Thus, the data were combined because of the very similar instruction.

4.2 Data collection

Students completed pre- and post-survey instruments as part of the design workshop experience. A total of 746 students completed both pre- and post-tests. A *conceptions of design* instrument, included as part of this pre/post-test was used to characterize changes in learners' prioritization and understanding of 20 design activities from "analyzing data" to "using creativity" (see Table 1). The instrument included three sets of questions: (a) given the list in Table 1 (in alphabetical order to reduce response bias) "select the five most important and five least important concepts for producing a high quality design", and (b) "for one of the five terms you marked as most important for producing a high quality, please explain why you believe it is important." (c) "for one of the five terms you marked as least important for producing a high quality, please explain why you believe it is not important."

4.3 Data analysis

A multi-method approach [24] was conducted employing both quantitative analysis of the Conceptions of Design Test (CDT) survey, and qualitative analysis of students' open-ended responses.

4.3.1 Quantitative analysis

To understand (RQ1) if students report changes in their perceived importance of "balancing trade-offs" after introduction of a design activity, we conducted McNemar's tests using data from the prioritization section of the CDT.

McNemar's tests were performed to determine whether proportions of "balancing trade-offs" priority increased from pre to post-test. This test is appropriate for paired dichotomous categorical data in which the p -value of the test would report if there were a significant difference between the two proportions [25]. This test provided a statistical measure of change in priority of "balancing trade-offs".

4.3.2 Qualitative analysis

In order to understand (RQ2) how students' *conceptions* of "balancing trade-offs" change after introduction of a design activity, the second phase of the multi-method approach started by identifying the students who explained the importance of "balancing trade-offs" in the open-ended question on the CDT. Please note that since students only

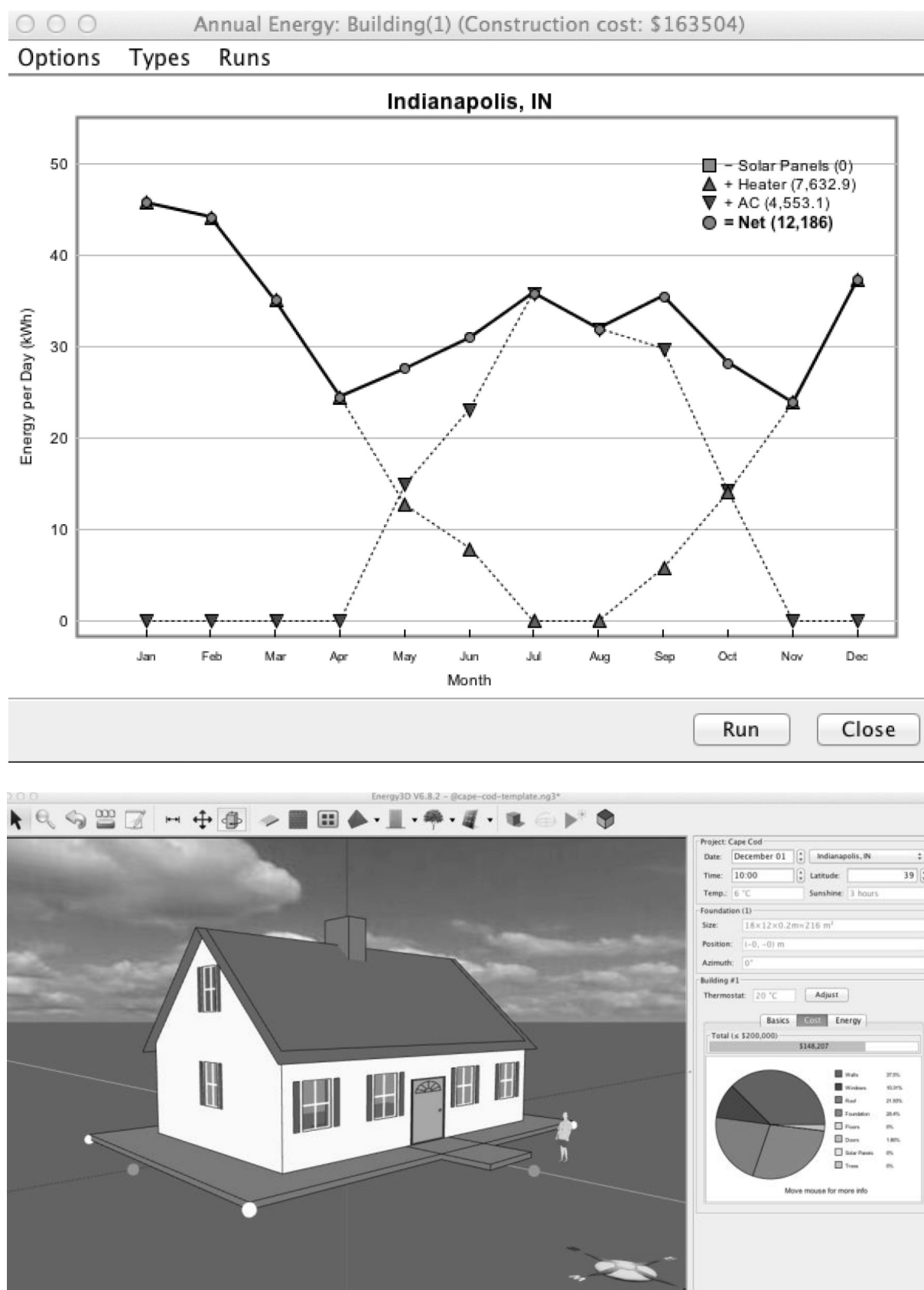


Fig. 2a-b. (Top) Example energy analysis of energy consumption per month in Energy3d, (Bottom) Example student design within Energy3D with house design and cost breakdown.

Table 1. Conceptions of Design Test (CDT)

List of Design Activities			Instructions
Analyzing data	Gathering information	Planning	<i>Selection:</i> Which 5 would you consider the MOST/LEAST important in terms of producing a high quality design <i>Open-ended response:</i> For one of the most/least important terms selected, please explain why
Balancing trade-offs	Generating alternatives	Prototyping	
Brainstorming	Identifying constraints	Reflecting	
Building	Iterating	Setting goals	
Communicating	Making decisions	Sketching	
Conducting tests	Modeling	Understanding the problem	
Evaluating		Using creativity	

Table 2. Frequency with which “balancing trade-offs” is described in open-ended responses

Test	IS Important	IS NOT Important	Total
Pre-	1	42	43
Post-	3	20	23
Total	4	62	66

had to describe one of their most/least important terms, the total number of times “balancing trade-offs” is described is much lower than the total times students indicated the term among the five terms that were MOST or LEAST important in design. The number of times the term was explicitly mentioned in the open-response is shown in Table 2.

A scoring rubric was used to systematically categorize students’ open-ended responses to describing balancing trade-offs in engineering design into four levels of understanding from (1) Understand importance of term, (2) Do not understand the term, (3) Show some understanding but indicate unimportance, (4) Researcher unable to decipher student intention.

5. Results and discussion

5.1 RQ1. Do students report changes in their perceived importance of “balancing trade-offs” after introduction of a design activity?

The analysis of change in students’ perceived importance of balancing trade-offs as a critical design practice compared percentages of students who selected trade-offs in the pre-test and post-test. Four percent (4.3%) of the students indicated “balancing trade-offs” as a MOST important term on the pretest, increasing to 5.5% on the post-test. Conversely, 52.1% of the students expressed “bal-

ancing trade-offs” was a LEAST important term on the pre-test, decreasing to 46% on the post-test.

An exact McNemar test showed that there was a statistically significant difference in the proportion of students who selected “balancing trade-offs” from pre- to post-test as a LEAST important term, $\chi^2 = (1, N = 746) = 6.33, p = 0.01$, but not as a MOST important terms, $\chi^2 = (1, N = 746) = 1.09, p = 0.30$. Thus, after the design project, “balancing trade-offs” was significantly less likely to be unimportant to students. Although “balancing trade-offs” was not necessarily a MOST important term, it was likely to land in the middle area of importance to the students.

5.2 RQ2. How do students’ conceptions of “balancing trade-offs” change after introduction of a design activity?

The scoring rubric results provided preliminary insights into students’ conceptualization of “balancing trade-offs.” Students responded in four ways: (1) Understand importance of term, (2) Do not understand the term, (3) Show some understanding but indicate unimportance, (4) Researcher unable to decipher student intention.

Of the 42 students who described “balancing trade-offs” as a LEAST important design concept on the pre-test, 25 students responded that they did not know or understand the term and therefore found it to be unimportant.

Others ($n = 5$) were able to relate trade-offs to design criteria but with a vague understanding. One student who described “balancing trade-offs” as a MOST important design concept on the pre-test answered with a vague understanding of the term:

“I think balancing trade offs is the best because you must understand if the price per performance is over one.”

Table 3. “Balancing trade-offs” change in priority from pre to post-test

	Number of Students Pre Test (%)	Number of Students Post Test (%)	P value	Effect size
Most Important	$n = 32$ (4.3%)	$n = 41$ (5.5%)	0.30	0.04
Least Important	$n = 389$ (52.1%)	$n = 343$ (46.0%)	<0.01*	0.10

** $p < 0.05$, *** $p < 0.001$.

This answer indicates the student is considering at least two factors in design quality, price and performance, with a vague numerical rating for the relationship between the two.

Of the 20 students who found “balancing trade-offs” as a LEAST important design concept on the post-test, 13 reported their rationale for selection as still not understanding the meaning of the term.

The remaining seven indicated varying conceptions and misconceptions of “balancing trade-offs”:

“I felt as though balancing trade offs is not an important element of making a high quality design because if they are trade offs, they must be of equal value and importance so it doesn’t really matter which one you choose.”

“Some ideas might be better than others so you want your design to be the best so u don’t want a trade off.”

“Balanced trading because not everything you do needs a balance trading.”

“Balancing trade offs just isn’t that important.”

“You don’t ever have a trade off with a house its you all are doing it or not.”

“I believe balancing off traits is the least important because the off traits can be useless.”

“Balancing trade offs is not that important because it does not do much to help.”

The three students who described “balancing trade-offs” as a MOST important design concept on the post-test began to show a more sophisticated understanding of the term. As the excerpts below demonstrate, these three students began to understand “balancing trade-offs” as an important decision-making tool, either in terms of selecting a concept/solution or identifying potential modifications:

“You have to balance the trade offs so you know what to improve on next time.”

“Balancing trade-offs because you often have to decide which is better between upgrades.”

“Balancing trade offs is important because its helps you understand pros and cons.”

Another alternative is that students might not have spoken to balancing trade-offs because they lack the language connection. Even if students are taking part in design activities that suggest they value balancing trade-offs, they might lack awareness of design terminology to understand what they are doing.

6. Conclusions & future work

A statistically significant fewer number of students found “balancing trade-offs” to be unimportant to design quality from pre- to post-test. However, their open-ended responses suggest that the term “balancing trade-offs” might be problematic despite the

relevance of making trade-offs to practicing designers and the use of this terminology in the Next Generation Science Standards. The engineering practices described by NGSS “incorporate specialized knowledge about criteria and constraints, modeling and analysis, and optimization and *trade-offs*” (emphasis added). Furthermore, the NGSS asks that high school students build on their middle school experiences of optimizing design solutions to “evaluate a solution to a complex real-world problem based on prioritized criteria and *trade-off* that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts” (emphasis added). Curriculum such as Engineering is Elementary (EiE) developed by the Museum of Science, Boston include trade-offs as an important reflection question for teachers to look for evidence of their students understanding and assessing trade-offs, specifically using the language of trade-offs. These examples suggest that trade-offs should be emphasized in engineering education of school children and that educators and students will come to a basic understanding of the language of design.

It is crucial for designers (including student designers) to make decisions based on the emphasis they place on particular design attributes. However, without explicit instruction of what trade-offs are and how to address them, students might not make the language connection. So, while students might be balancing trade-offs, they might not have the terminology to know that is indeed what they are doing. Moreover, students might not fully understand how their focus on particular outcomes or costs affects their design decisions or understand their role in shaping their design solutions.

As engineers, we forget that “balancing trade-offs” is jargon and as such carries a very specific meaning in our community. In our current work, we have gone back to the ideas in trade-offs and have looked for additional ways in which to express these ideas by reviewing student open-ended responses and talking with teachers in the middle school classrooms. In the latest cycle of data collection in the classroom we have revised problematic language in the survey to be more descriptive, including a revision to “balancing trade-offs (considering strengths & weaknesses).” Forthcoming analysis will investigate students’ conceptions with revised language.

Future work will look at students’ design artifacts to understand if they balanced trade-offs of aesthetics, cost, and energy efficiency as they addressed the design challenge. Additionally, we will investigate the extent to which students’ perceived importance of “balancing trade-offs” (considering

strengths & weaknesses)” on this Conceptions of Design Test reflects their design behaviors as collected from log data of their design process. This will allow us to understand if students do what they say is important in design. We plan to triangulate our findings with additional sources of data such as student interviews and design artifacts to better understand how well the Conceptions of Design Test (CDT) assesses design conceptions of students in areas including and beyond “balancing trade-offs.” Because this tool requires little time from students to complete and is relatively straightforward for educators to assess it could be an effective and efficient design assessment tool.

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Appendix A

Design Challenge

Solar House Design Challenge

Design Challenge

Wouldn't it be great if our homes and offices did not need to consume energy? Or what if your home actually produced energy and was able to provide this energy back to the grid? To meet this ambitious goal, new buildings must be able to produce as much energy as possible to meet their occupants' needs. The key to finding a solution to this challenge is figuring out a way to take advantage of the free and unlimited energy from the sun without compromising the thermal comfort of our homes, schools, and office buildings.

Energy3D Homes needs your help to design an energy efficient model house that is able to maintain a comfortable interior temperature for its occupants all year long. Create a house that satisfies all the following criteria and constraints.

Criteria

- Minimize energy needed to keep the building comfortable on a sunny day or a cold night (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

In addition, there are geometric and budget limitations:

- 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 to be 20°C all the time.
- The house's platform must not exceed the 28 × 36 m platform provided in the software.
- Tree trunks must be outside 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.

Overview

You will create and evaluate *three unique house designs* using the Energy3D Software. You will then use a rating chart and your test results to determine which of your three designs you believe best meet the criteria and constraints set by the design challenge. Finally, you will present your house to the class and explain its virtues and drawbacks.

Comparing House Options with Evidence

	House Option 1	House Option 2	House Option 3
Image of House (Screenshot) Northeast View			
Southwest View			
ATTRACTIVENESS/DESIRABILITY			
List features that make the house attractive/desirable			
Total area of house (m ²) (floor)			
Average height of walls (m)			
Estimated volume of house (m ³) (area × avg. height)			
Total Area Windows [m ²]			
Total Surface Area House [m ²] (area of all exterior walls)			
Window-to-Wall Ratio (Total area window/total surface area house)			
Each side of house have window?			
<40 solar panels?			
House temp 20°C?			
Any overhanging solar panels?	yes/no	yes/no	yes/no
ENERGY			
Annual Energy Consumption (kWh)			
Energy	low/medium/high	low/medium/high	low/medium/high
COST			
Total Cost (\$)			
Cost of house <\$60,000	under/over	under/over	under/over
Cost / Volume [\$ / m ³]			
Cost/Volume [\$ / m ³]	low/medium/high	low/medium/high	low/medium/high

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