Characterizing Trade-off Decisions in Student Designers

Molly Hathaway Goldstein

Purdue University

Follow this and additional works at: https://docs.lib.purdue.edu/open_access_dissertations

Recommended Citation
https://docs.lib.purdue.edu/open_access_dissertations/1937

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.
CHARACTERIZING TRADE-OFF DECISIONS IN STUDENT DESIGNER

by

Molly Hathaway Goldstein

A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

School of Engineering Education
West Lafayette, Indiana
August 2018
THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Robin S. Adams, Co-Chair
    School of Engineering Education
Dr. Şenay Purzer, Co-Chair
    School of Engineering Education
Dr. Morgan Hynes
    School of Engineering Education
Dr. Joyce Main
    School of Engineering Education
Dr. Shane Tutwiler
    School of Education, University of Rhode Island

Approved by:
    Dr. Donna Riley
    Head of the Graduate Program
To my parents for always believing in me.

And to Matt whose confidence in me and support made this work possible. It is a gift to be able to dream in the same direction with another person. I’m looking forward to continuing this journey with you!
ACKNOWLEDGMENTS

I would like to first acknowledge my dissertation advisors, Dr. Robin S. Adams and Dr. Şenay Purzer. I knew on my first visit to Engineering Education at Purdue University that I wanted to do my dissertation work with one of them, but I never dreamed I would have the good fortune of being co-advised by both. Robin and Dr. Purzer have provided me with direction, encouragement, and guidance since joining the School, and have been assiduous in their efforts to advance my research and future career. Robin has incredible insight, and always provides thoughtful comments to improve our work. I appreciate the efforts she has taken to mentor me not only in my dissertation work, but also in faculty apprenticing History & Philosophy of Engineering Education, and in our collaborative DTRS work. Dr. Purzer provided exemplary mentoring on our first co-authored publication, and continues to inspire me to keep a strong research record. Her encouragement and support to present work at REES in Dublin lit a spark in me as one of the biggest “aha!” moments in my PhD for which I will always be appreciative.

I want to also thank my extraordinary committee members: Dr. Morgan Hynes, Dr. Joyce Main, and Dr. M. Shane Tutwiler. Dr. Hynes’ focused questions about the human component of design during my Readiness Assessment had great impact on the direction of my work. Dr. Main’s thoughtful feedback helped me formalize my methods. Dr. Tutwiler came onboard in the eleventh hour, and provided immense statistical support for which I will be forever grateful.

The administrative support from ENE, but especially Loretta McKinnis and Carol Brock, made graduate school so much easier to navigate. From a friendly “hi!” in between classes to tracking down faculty schedules – I don’t know how we could do anything without you!

I will be eternally grateful for the camaraderie from my cohort. I have learned so much from Catherine, Emilie, Monique, Natascha, Neha, and Trina and continue to learn more from them each month. I look forward to future collaborations! While Richard, Nick, and Avneet aren’t part of my cohort, their conversations and perspectives were so helpful to this work and my broader thinking about engineering education.

I would also like to acknowledge all of the coauthors and others who have contributed to this work. Specifically, Sharifah Omar (currently an undergraduate studying Agriculture & Biological Engineering at Purdue) has been a tremendous help in managing the vast amount of
data collected. Her tremendous work ethic, attention to detail, and passion for engineering education work has been invaluable to the success of this research.

I owe a great deal of my interdisciplinary story to my parents who always thought (and still do!) that I can do anything… and lots of things. When I told them I wanted to be a singing, dancing, doctor in preschool they encouraged all of it – from driving me around and encouraging me to try new things, while always listening to me. Thank you for molding so much of who I am. I hope I make you proud.

Mark, Katie, and James – thank you for being my best friends during the most formative years of my life and continuing to support me through each new stage of life.

I would not have left industry to pursue my dream of earning a PhD and would not have been able to finish successfully without the love and support (& push!) from my husband. Words can’t even begin to express how much I love you and how grateful I am for your support. Thank you for being my co-pilot along this crazy ride! Jack, Audrey, and Leo – thank you for helping me keep perspective throughout this whole process. Even though I am so proud to be earning my PhD, it pales in comparison to the absolute pride I have for each of you. Each of you is exactly what I hoped and prayed for, and you are my true joys in life.

This work would not have been possible without the collaboration of the dedicated teachers and enthusiastic students at my partner schools. I also would like to express my gratitude to the Concord Consortium for their innovative software and support, especially Charles Xie, Jie Chao, and Corey Schmipf.

A final word of appreciation to all of the funding agencies that have enabled me to pursue this endeavor. This work presented in this dissertation 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 material are my own and do not necessarily reflect the views of the funding bodies.
PREFACE

“You don’t write because you want to say something, but because you have something to say.” - F. Scott Fitzgerald

My personal interest in pre-engineering students’ decision-making, specifically their trade-off behaviors stems from my first extensive design experience. The preeminent breast pump company in the world sponsored my capstone design project. My team of three was tasked with designing a tool with which the company could test their pumps as an alternative to real, lactating mothers. This design project was very open-ended, ill-defined, and involved design decisions at every turn. I saw a meaningful application in balancing benefits and trade-offs. How could we design something that was very customizable while also being portable? How could we design for durability, varying flow rates, and work within our small budget? While I knew that engineering design work was what defined engineering, the process of negotiating these design elements and finding the right balance is where I found a thrill. Later when I worked as an environmental engineer I found trade-offs even more wrought with high stakes. A favorite project of mine involved helping a utility company work through regulations from the Environmental Protection Agency to improve air quality in national parks. I worked with my clients to frame the problem, gather information, and run analyses to understand the relationship between incremental visibility improvements in Hawaii Volcanoes National Park and Haleakala National Park, reductions in tons of air pollutants, costs of control measures, and timing of efforts. This massive undertaking came down to understanding and balancing tradeoffs, while communicating this balance to the EPA. Making our very technical analysis transparent to various stakeholders was very meaningful to my growth as a designer and an educator.

My research objectives in my dissertation continue my interests in trade-offs in engineering design. This work seeks to understand the relationship between the degree to which a design embodies trade-offs and students’ design thinking. My primary reason for pursuing this work is to understand how students make trade-offs in pre-engineering work so that we can offer better trade-off learning at pre-college and college levels. Not only will advancing their trade-off skills make them better engineers, an understanding of the central importance of sound decisions in engineering might encourage these students to pursue engineering in the first place.
TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................................................... xii
LIST OF FIGURES .......................................................................................................................................... xiii
RELEVANT TERMINOLOGY ........................................................................................................................... xv
ABSTRACT ....................................................................................................................................................... xvi
CHAPTER 1. DISSERTATION OVERVIEW ........................................................................................................ 1
  Introduction ................................................................................................................................................ 1
  Background ................................................................................................................................................. 2
    Engineering design involves decision-making and trade-offs ............................................................... 3
    Importance of students’ abilities to make design trade-off decisions ................................................. 4
  Methods ..................................................................................................................................................... 6
    Research participants and classroom context ...................................................................................... 6
    Design challenge .................................................................................................................................. 7
    Energy3D software environment ........................................................................................................... 9
    School Implementations ....................................................................................................................... 10
  Data sources ............................................................................................................................................. 14
    Process data ......................................................................................................................................... 14
    Design artifacts ..................................................................................................................................... 15
    Student design rationale ...................................................................................................................... 16
    Conceptions of Design Test (CDT) ....................................................................................................... 18
  Chapter Organization ............................................................................................................................... 19
  Contribution .............................................................................................................................................. 21

CHAPTER 2. UNDERSTANDING MIDDLE SCHOOL STUDENTS’ CONCEPTIONS OF TRADE-OFFS IN DESIGN ...................................................................................................................... 23
  Abstract ................................................................................................................................................... 23
  Introduction ............................................................................................................................................. 24
  Literature review .................................................................................................................................... 25
    Engineering design ............................................................................................................................... 25
    Trade-offs in engineering design ........................................................................................................... 26
    Conceptual framework ......................................................................................................................... 28
Methods .................................................................................................................................... 28

Participants & Design challenge .................................................................................................. 29

Data collection ................................................................................................................................ 31

Data analysis ...................................................................................................................................... 32

- Quantitative Analysis .................................................................................................................... 32
- Qualitative Analysis ....................................................................................................................... 32

Results & Discussion .......................................................................................................................... 33

- How do students’ perceived importance of “balancing trade-offs” change after introduction of a design activity? .................................................................................................................................................. 33
- How do students’ conceptions of “balancing trade-offs” change after introduction of a design activity? .................................................................................................................................................. 34

Conclusions & future work .................................................................................................................. 35

Acknowledgments ............................................................................................................................. 37

CHAPTER 3. A MEASURE OF DESIGN ARTIFACT QUALITY TO ENCOMPASS MULTIPLE DIMENSIONS: AN EMPIRICALLY-BASED METHOD .................................................................................................................. 38

Abstract ......................................................................................................................................... 38

Introduction & Motivation .................................................................................................................. 39

Guiding Question .............................................................................................................................. 40

Conceptualizing a multidimensional idea of trade-off ........................................................................ 40

Linking trade-offs to design competency ............................................................................................ 43

Examining approaches to measuring quality that guide the trade-off value protocol ......................... 44

- Designer tools to assess design artifact quality ............................................................................ 44
- Design researcher tools to assess design artifact quality ................................................................. 50

Opportunity for a new perspective in measuring design quality ......................................................... 53

Trade-off Value Protocol .................................................................................................................... 54

- Quality score pilot ......................................................................................................................... 55
  - Pilot study lessons learned ............................................................................................................ 56

Trade-off Value approach .................................................................................................................... 57

Methods ............................................................................................................................................. 58

- Students and Design Challenge .................................................................................................... 58

Data sources and Collection ................................................................................................................ 60
CHAPTER 4. AN INVESTIGATION OF THE RELATIONSHIP BETWEEN STUDENT DESIGN RATIONALE AND QUALITY OF DESIGN SOLUTION

Abstract

Introduction & Motivation

Background and Theory

Design is central to engineering and engineering education

Engineering design involves decision-making and trade-offs

Importance of students’ abilities to make design trade-off decisions

Teaching trade-off decision-making and evaluative judgement

Conceptual Framework: Understanding student trade-off decisions

Research Methods

Students and Design Challenge

Data Sources

Design artifacts

Design Rationale Elicitation Task

Data Analysis

Experiential Trade-offs through Calculation of Trade-off Value Score
Pattern Identification: Cluster analysis ................................................................. 101
Results ...................................................................................................................... 102
Descriptive analysis of design rationale and design quality ................................. 102
Relationship between design rationale and design solution quality ...................... 103
   High dual-process trade-offs student case ............................................................ 106
   Analytical-Dominant trade-offs student case ....................................................... 108
   Experiential-Dominant trade-offs student case ................................................... 109
   Low dual-process trade-offs student case ............................................................ 110
Discussion ................................................................................................................. 111
   RQ1: To what extent do pre-engineering students understand trade-off decisions as evidenced through ability to evaluate alternative solutions by considering multiple trade-off factors?

   RQ2: What are the patterns of design trade-off decision in pre-engineering students? .... 113
      High Dual-Process Trade-offs Cluster................................................................. 113
      Analytical-Dominant Trade-offs Cluster .......................................................... 114
      Experiential-Dominant Trade-offs Cluster ....................................................... 115
      Low Dual-Process Trade-offs Cluster ............................................................... 115
Conclusion & Implications ....................................................................................... 116
Limitations & Future Work ...................................................................................... 117

CHAPTER 5. SUMMARY, IMPLICATIONS AND FUTURE RESEARCH DIRECTIONS .... 119
Overview ................................................................................................................... 119
Design trade-offs are an important educational and research focus ......................... 119
Chapter summaries ................................................................................................. 120
   Study 1: Prioritizing Trade-offs ......................................................................... 120
   Study 2: Enacting Trade-offs ............................................................................. 121
   Study 3: Reasoning about Trade-offs ................................................................. 122
“Conversations” between chapters ......................................................................... 123
Contribution ............................................................................................................. 123
Implications: The value of characterizing student design trade-off decisions in engineering education ................................................................. 125
Future Work ............................................................................................................. 127
LIST OF TABLES

Table 1. Student samples associated with dissertation chapters ..................................................... 7
Table 2. Design challenge criteria and constraints ........................................................................... 8
Table 3. Key implementation characteristics summary .................................................................... 14
Table 4. Energy3D action schema ................................................................................................ 15
Table 5. The trade-off factors associated with building data........................................................ 17
Table 6. Conceptions of Design Test (CDT) .................................................................................. 31
Table 7. Frequency with which “balancing trade-offs” is described in open-ended responses .... 32
Table 8. “Balancing trade-offs” change in priority from pre to post-test ........................................ 34
Table 9. Summary of dimensions in designer tools used to assess quality .................................... 49
Table 10. Summary of dimensions in researcher tools used to assess quality .............................. 52
Table 11. Summary of dimensions in designer & researcher tools used to assess quality ........... 54
Table 12. Trade-off framework with associated log data ............................................................. 57
Table 13. Design challenge criteria and constraints ................................................................... 59
Table 14. Trade-off framework with associated log data ............................................................. 60
Table 15. The trade-off factors associated with building data....................................................... 98
Table 16. Design Rationale Elicitation Task trade-off coding scheme ........................................ 99
Table 17. Sample student responses to the Design Rationale Elicitation Task ......................... 100
Table 18. Descriptive statistics of Trade-off Value and Design Rationale Levels ...................... 102
Table 19. Design Rationale Elicitation Task score breakdown .................................................... 103
Table 20. Trade-off cited in Design Rationale Elicitation Task .................................................... 103
Table 21. Student cases of trade-off clusters with Trade-off Value score and design rationale. 105
LIST OF FIGURES

Figure 1. Meta-level preview of literature ................................................................. 3
Figure 2. Student design challenge prompt................................................................. 8
Figure 3. Energy3D, a CAD platform for designing, analyzing, and constructing green buildings that utilize renewable energy ............................................................ 10
Figure 4. Students designing using Energy3D in computer labs at School A .......... 12
Figure 5. School B top designers with Purdue design review team.................... 13
Figure 6. Timeline of design project and data collection at Schools A & C .......... 13
Figure 7. Images of design artifacts and performance data .................................. 16
Figure 8. The open-ended design rationale question students used in pre and post-test .... 17
Figure 9. Conceptions of Design Test (CDT) .......................................................... 19
Figure 10. Overview of three studies ................................................................. 20
Figure 11. Trade-off value conceptual framework ................................................. 28
Figure 12. (Top) Example energy analysis of energy consumption per month in Energy3d, (Bottom) Example student design within Energy3D with house design and cost breakdown .... 30
Figure 13. Mr. Coffee® design trade-offs .............................................................. 41
Figure 14. Moccamaster® design trade-offs ......................................................... 42
Figure 15. Trade-off Value conceptual framework .............................................. 42
Figure 16. Example House of Quality visual (from Hauser & Clausing, 1988) .... 46
Figure 17. Axiomatic Design depiction (adapted from Suh, 1990) ...................... 47
Figure 18. Trade-off Value sample distribution box plot ........................................ 63
Figure 19. Student EMS_C018 design artifact .................................................... 65
Figure 20. Student EMS_C006 design artifact .................................................... 65
Figure 21. Student EMS_C018 artifact performance relative to sample .............. 66
Figure 22. Student EMS_C006 artifact performance relative to sample .............. 66
Figure 23. Student EMS_B025 design artifact .................................................... 68
Figure 24. Student CLMS_C313 design artifact ................................................. 68
Figure 25. Student EMS_B025 artifact performance relative to sample .............. 69
Figure 26. Student CLMS_C313 artifact performance relative to sample .......... 69
Figure 27. Student EMS_B014 design artifact .................................................... 71
RELEVANT TERMINOLOGY

Attribute: Any property or characteristic of a design artifact (e.g. cost, efficiency, etc.)

Design artifact: The digital or physical representation of a design. This can include 2D drawings and 3D models and can be physical or virtual.

Design constraint: A limitation or condition that must be satisfied in addressing a design problem. Is measured in a binary way.

Design criteria: A function, property, or performance standard/attribute of a design solution that can be measured.

Design alternative: One of multiple solutions to a design problem

Optimization: Maximizing or minimizing a particular design dimension to ensure the best performance possible for that dimension

Performance level: A quantitative measure of an attribute (e.g. 50 kWh, $250,000)

Trade-off: A type of decision that requires the decision-maker weigh possible outcomes against their respective shortcomings in areas such as cost, degree of safety, and various performance indicators
ABSTRACT

Decision-making and design in uncertain situations in which information is limited and goals are ambitious or conflicting are a part of common practices of engineers. Such abilities in engineering practices are important to develop for all students from elementary school through college and graduate school. An important aspect of decision-making in design are the trade-offs decisions designers make throughout a project. Trade-offs are a complex element of a decision, that involves weighing possible outcomes against their respective benefits and costs in areas such as aesthetics, cost, degree of safety, and various performance indicators. Making trade-off decisions is an effective design practice, and is a key dimension of successful performance. Understanding how students characterize their design tradeoffs would allow educators a better glimpse into students’ design thinking. Each chapter of this dissertation provides unique insights on students’ conceptions, performance, and explanations of trade-off decisions and the patterns of variation among these parameters.

The first study investigates how students describe and prioritize design trade-off decisions through the following research questions: Do students report changes in their perceived importance of making-trade-offs after a design project, and if so, how do their conceptions change? A McNemar test was used to statistically analyze pre and post changes on a Conceptions of Design Test. I found that significantly fewer students ranked trade-offs to be a LEAST important design activity (n=746). In a thematic analysis of open-responses where students explain their ranking, I found many students did not understand either the idea or the terminology of “trade-offs”, despite the relevance of making tradeoffs to practicing designers and the use of this terminology in the Next Generation Science Standards. 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 on the role of trade-offs in design and how to manage trade-offs, students may
struggle with linking intuitive trade-off decision making with the terminology of “balancing trade-offs” that references an explicit design strategy.

The second study seeks to understand and measure how students “do” trade-offs in design. Central to this study was developing a way to depict design artifact quality that: (1) encompasses multiple complementary and competing dimension, (2) can be applied consistently and systematically, and (3) is indicative of design competency. I developed the Trade-off Value protocol which assesses design artifacts in the areas of human, technical, and economic factors. The Trade-off Value is calculated as the sum of percentile ranks of student performance relative to their class. I analyzed approximately 400 student design artifacts to test the Trade-off Value protocol and calculated Trade-off Value scores for each design to investigate patterns of variation in the quality of students’ artifacts. Results suggest the Trade-off Value Protocol is a useful tool for three reasons. First, because it is conceptually grounded in the definition of design, it provides a comprehensive way to think about the interaction of client/user priorities, design possibilities and objective measures. Second, the protocol while being systematic is also easy to use. Third, the Trade-off Value protocol represents an important feature of design competency with which beginning designers struggle. In addition, using an etic approach to thematic analysis of the student design artifacts, I identified five distinct patterns of variation in artifact quality which suggests patterns in ways students address multiple complementary and conflicting design dimensions that indicates variations in design trade-off competency.

The third study provides a look at how students explain trade-offs in design and the relationship between how students “do” and explain design trade-offs. Through the context of an in-class individual design challenge, I collected data from 318 middle school students including (1) the final design products, and (2) a post-challenge design reasoning elicitation problem. I characterized patterns of student trade-offs through the Dual-Process Framework for Evaluating Student Design Trade-offs. The analysis started with the calculation of artifact quality score (called Trade-off Value) for each student and the scoring of the design reasoning elicitation problem through a content analysis of student responses. I used a cluster analysis to identify groups exhibiting distinct patterns of trade-offs as evidenced from these two scores. Results suggest that students were able to understand trade-off decisions consistent with beginning designers, and that
students fit into four main patterns of their approaches in experiencing and analyzing trade-off decisions. Findings may be used by educators to understand variation in students’ trade-off profiles that might affect deeper learning.

Taken together, the results from these inter-related studies with over 1,000 students highlight the variation of pre-engineering students’ design trade-offs with respect to how students value, understand the language of, enact performance of, and provide their reasoning in order to start building a theory of trade-offs in student designers. This level of understanding is critical so that teaching efforts start from an understanding of what students currently do and know in order to address opportunities to encourage important student growth in not only the direction of engineering design but more importantly as contributors in innovating through global challenges.
CHAPTER 1. DISSERTATION OVERVIEW

Introduction

Decision-making and design in uncertain situations in which information is limited and goals are ambitious or conflicting are a part of common practices of engineers (Howard & Abbas, 2016; National Research Council, 2001; Otto & Antonsson, 1991). Such abilities in engineering practices are important to develop for all students from elementary school through college and graduate school. An important aspect of decision-making in design are the trade-offs decisions designers make throughout a project. Trade-offs are a complex element of a decision, that involves weighing possible outcomes against their respective benefits and costs in areas such as aesthetics, cost, degree of safety, and various performance indicators (Otto & Antonsson, 1991). As a core element of design, the practice of design trade-offs must be explicitly taught as part of design education.

Although much is understood about professional designers’ behaviors as compared to novice designers such as students (Atman et al., 2007; Crismond & Adams, 2012; Cross, 2003; Mentzer, Becker, & Sutton, 2015), there is little research on how students make trade-off decisions while designing. Prior studies have identified student challenges in understanding scoping problems (Atman et al., 2007; Hsu, Cardella, & Purzer, 2010), in gathering appropriate information (Atman et al., 2007), as well as supporting their design decision with data (Cole & Mckenna, 2010; Younker & McKenna, 2009). However, while making trade-off decisions is a necessary design practice, and is a key predictor of successful performance (Crismond & Adams, 2012), research on trade-off decisions has demonstrated that students struggle with trade-offs. These studies indicate that students do not effectively make design trade-off decisions because they do not fully detail design options (Younker & McKenna, 2009), do not understand how to manage conflicting criteria (Girod, Elliott, Burns, & Wright, 2003), and fail to evaluate data pertinent to trade-offs (Fila & Purzer, 2013). While these studies show student difficulties in making trade-offs, a better understanding of how students enact trade-offs in the concrete or particular case and abstract or general case would allow a more comprehensive characterization of patterns of trade-offs behaviors in student designers. Without such knowledge at the K-16 level, we cannot create
suitable design activities for students to improve on their decision-making skills, inhibiting their effectiveness as contributing members of society, and for some students as future engineers.

My long-term goal is to understand design trade-off behaviors among pre-engineering students and engineering students. To examine authentic trade-off processes, I will study how students solve engineering design problems in which students design virtual homes using a simulation tool. The design environment, with engineering and socio-scientific complexities, enables collecting a rich dataset on students’ design trade-off behaviors, which includes logs of student design files, as well as digital notebook reflections in which students justify their design decisions. Learning analytics, design artifacts, traditional tests and reflections will be used to characterize students based on the patterns they exhibit related to trade-off decisions. Identifying these patterns will help K-16 educators (1) understand variations in student trade-off behaviors and associated performance, and (2) incorporate appropriate design activities into their curricula. By introducing these trade-offs associated with engineering design earlier, I hope that students will become more inherently interested in engineering.

**Background**

This dissertation presents three studies that work together to characterize student trade-off decision. In doing so, each of the three papers goes deeper into the literature required situation each of the studies’ goals. The concept map in Figure 1 provides a meta-level preview of the literature involved in the three studies.
Engineering design involves decision-making and trade-offs

Making decisions is an important part of much engineering work. In fact, some describe design as a series of decisions (Ullman, 2001) noting that design problems require a designer to make many decisions throughout the entire design process (Akin & Lin, 1996). In a meta-synthesis of literature highlighting the differences in behaviors of beginning versus informed (or “engaged and knowledgeable”) designers, Crismond & Adams (2012) discuss “weigh options and make decisions” as one of the nine critical design practices. In particular the behavior of “weigh options and make decisions” is a distinguishing area for informed designers in terms of decision-making skill. Practicing designers work through complex and ill-structured problems that require both weighing options and forecasting the impact of these decisions (Strobel & Pan, 2010). Informed designers are skilled at “weighing and articulating” (Crismond & Adams, 2012, p. 761) both the pros and cons of a particular design solution, and can look for trade-offs in even the best ideas.

Trade-offs are a complex element of a decision, as the decision-making weighs possible outcomes against their respective costs (Otto & Antonsson, 1991). Although trade-offs in design are inevitable (Wong, Lam, & Chan, 2009), a design process where designers can examine trade-
offs and develop alternatives is likely to lead to a higher quality design solution. The National Research Council (2001) 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 tradeoffs. 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” (NRC, 2001, p. 10).

Studying engineers in the workplace has suggested the importance of making trade-offs as a professional skill. In one such study (Jonassen, Strobel, & Lee, 2006) highlighted the importance of balancing competing needs and criteria as one of the attributes that differentiate workplace problems from school problems. In another investigation, Strobel and Pan (2010) examined engineering workplace problems through a multi-case comparison of 90 engineers and found engineers weigh options and estimate 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. Furthermore, practicing engineering designers not only make trade-off decisions, they also communicate their “optimization approach” to clients (Wong et al., 2009), including internal team members and external stakeholders.

**Importance of students’ abilities to make design trade-off decisions**

Decisions are an integral part of engineering education at the undergraduate level. In fact, the Accreditation Board for Engineering and Technology (ABET) in specifying curriculum requirements (Criterion 5) define engineering design as:

“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” (emphasis added)

ABET also specifies that a crucial student outcome (Criterion 3) of an undergraduate engineering education includes:
“an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability”

Working within the constraints of economic, environmental, social, and more requires trade-off decisions. Therefore, ABET is requiring the students make effective design trade-off decisions upon completion of their engineering degree because it is an essential engineering practice.

Studies conducted in a college setting highlight large differences between the design processes of expert designers and the habits of undergraduate students. People in general, not only students, struggle with evaluating trade-offs between two attributes of very unequal importance where the option should be “obvious” (Scholten & Sherman, 2006), demonstrating that decision-making is not necessarily a naturally easy process. Prior studies with engineering college students identify weaknesses, especially in making trade-off decisions. For example, Younker and McKenna (2009) found that only 31% of first year engineering design teams supported their decisions with evidence, relying more extensively on self-generated assumptions rather than performance data. Girod and colleagues (2003) showed that design teams spent little time discussing the relative importance of design criteria. Implications from both studies indicate that students do not fully characterize their design options and do not reliably understand how to manage conflicting criteria.

Because engineering students experience challenges in making trade-off decisions, it is likely that pre-engineering students also face similar challenges. Despite the perceived difficulty, the development of decision-making skills and trade-off aptitude is broadly recognized as a significant learning objective at the K-12 level. The International Technology and Engineering Educators Association (ITEEA, 2007) describes what students should know and be able to do in order to be technologically literate in Grades K-12, with optimization and trade-offs noted as “core concept of technology” for students because of society’s growing interdependency with technology. ITEEA (2007) contends that students need repeated exposure in determining trade-offs due to the importance of this skill and prevalence that trade-offs will be encountered. Similarly, the importance of trade-off skills in linking science knowledge with design knowledge is outlined in the Next Generation Science Standards (NGSS) (Achieve, 2013) Disciplinary Core Ideas (emphasis added):
ETS1.C: Optimizing the Design Solution

- Although one design may not perform the best across all tests, *identifying the characteristics of the design that performed the best* in each test can provide useful information for the redesign process—that is, some of those characteristics may be incorporated into the new design. (MS-ETS1-3)

- The iterative process of testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution. (MS-ETS1-4)

- **Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed.** (HS-ETS1-2)

At both the middle school and high school levels, this disciplinary core idea involves using judgement to compare and improve on proposed design solutions. By the end of middle school, students should be able to evaluate solutions with respect to how well they meet criteria and constraints to systematically understand why features in a particular design solution might perform “best.”

**Methods**

This research was conducted as part of a larger study that examines student learning in design. The name of the larger study is Collaborative Research: Large-Scale Research on Engineering Design Based on Big Learner Data Logged by a CAD Tool and is funded by National Science Foundation (NSF) under Grant DUE #1348547 and DUE #1348530.

**Research participants and classroom context**

These studies were conducted at three middle schools in the Midwest, United States with a total of 746 students, ages (12-14) involved in the Spring of 2016, and at two middle schools for a total of 398 students the Spring of 2017. Table 1 represents the number of research participants and schools associated with each of the three studies in this dissertation conducted over two years.
Table 1. Student samples associated with dissertation chapters

<table>
<thead>
<tr>
<th>Paper</th>
<th>School(s)</th>
<th>Year of data collection</th>
<th>Number of students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prioritizing Trade-offs</td>
<td>A, B, &amp; C</td>
<td>2016</td>
<td>746</td>
</tr>
<tr>
<td></td>
<td>A &amp; C (suburban &amp; urban)</td>
<td>2017</td>
<td>398</td>
</tr>
<tr>
<td>Enacting Trade-offs</td>
<td></td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>Reasoning about Trade-offs</td>
<td>A (suburban)</td>
<td>2017</td>
<td>318</td>
</tr>
</tbody>
</table>

Schools A & B are located in an affluent suburb outside of Indianapolis, IN, and is resource rich in terms of teachers and tools. School C is an inner-city school located in Hammond, IN with a very diverse student population in terms of race and ethnicity. School C has limited resources, and the vast majority of students qualify for free and reduced lunch. Each of these three schools will be described in more detail in the implementation section.

The design project is part of the students’ curriculum, which means all students participating in the class were eligible for participation in the study. Purdue Institutional Review Board (IRB) approved this human subject research, including parental consent forms and student assent forms. These forms were provided in both English and Spanish to accommodate a diverse set of parents and students and are provided in the Appendix A. Details regarding the design challenge and the schools are provided in the following paragraphs.

**Design challenge**

The design challenge (See Figure 2 and Table 2) presented to students asked them 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 with specific criteria and constraints. Students were instructed to create high quality home designs that attempted to balance energy consumption, construction cost, livability, and aesthetics. The design challenge targeted the domain of green building science, a multi-disciplinary field that integrates physics, earth sciences, geometry, and systems thinking (Chao et al., 2017). As a whole, the design project was concerned with minimizing energy, but different elements of the design work together in
service of that goal as well as other goals (e.g. maintaining low construction costs). The systems thinking required in the design project (of interconnected elements in service of meeting multiple criteria) exemplified trade-off decisions as students were tasked with designing a home with complementary and conflicting criteria that were technical, human, and economical. This was an authentic problem-solving experience for students as it included multiple, conflicting goals with competing criteria (Jonassen, Strobel, & Lee, 2006). Students were instructed to create three iterations of their design, and were free to choose when to start working on one design or another.

Figure 2. Student design challenge prompt

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>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)</td>
<td>Cost cannot exceed $250,000 in building materials</td>
</tr>
<tr>
<td>Minimize total cost of the building</td>
<td>Each side of the house must have at least one window.</td>
</tr>
<tr>
<td>Comfortably fit a 4-person family (approximately 2200 ft² or 204 m²)</td>
<td></td>
</tr>
<tr>
<td>Has an attractive exterior and is desirable</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Design challenge criteria and constraints
Table 2 continued

- 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 x 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.

Energy3D software environment

The energy-efficient design challenge introduced at both schools involved using Energy3D to design single-family homes. Energy3D is a free, open-sourced computer-aided design platform (http://energy.concord.org/energy3d/) that allows students to design and build energy efficient buildings (see Figure 3). This software is user-friendly and was developed with educational research purposes in mind. As students design in Energy3D, a logger collects their process data behind the scenes (i.e., all user interactions with the software). In addition to fine-grained process data (such as edit window, add solar panel, etc.), design specifics for the final design (e.g. cost, dimensions, energy consumption) are also collected within the Energy3D platform.
Figure 3. Energy3D, a CAD platform for designing, analyzing, and constructing green buildings that utilize renewable energy

In Energy3D, users can quickly sketch up a realistic-looking building and evaluate its energy performance for any given day and location. Energy3D can rapidly generate cost charts, time graphs, heat flux, and heat maps for in-depth analyses. An embedded notepad is available for keeping design journals. Fine-grained data information of student actions, experimentation results, electronic notes (i.e. reflections), and design artifacts are collected through automatic, unobtrusive logging as students design.

School Implementations

Three schools participated in the project: Students at School C worked individually under the guidance of one science teacher over the course of two weeks of approximately 50-minute
classes to design two to three unique solutions to the design prompt. These students were in 8th grade, and thus were mostly 13-14 years old. The science teacher had over 25 years of experience teaching general science courses and four years of experience teaching engineering and modeling with Energy3D. The teacher introduced the software and design challenge to the students on laptops loaned to the teacher from Purdue University. Computer lab space was quite limited at School C, and borrowing computers allowed the teacher to give students access to the design challenge consistently over two weeks. I made instructional videos of the software and shared with the teacher for: (1) consistency with my teaching demonstration, (2) a resource for absent students or students who wanted a refresher in designing. These videos provided an overview of Energy3D software and instructed students how to build and use analysis tools within Energy3D. In addition, these videos were structured to provide mini challenges for the students. In the first challenge, students guided to build a house, run an energy analysis and a cost analysis, then record their results in the note feature of Energy3D. The second challenge required students modify their home through window placement, tree addition, home material, etc. in an effort to reduce energy. Students were then instructed to make note of their design iteration and resulting analyses. The third challenge allowed students to use solar panels in order to affect their house energy and cost. Students were guided to also record their actions and analyses from this third challenge. The teacher instructed students to use the “notes” tool within the Energy3D software to reflect as they designed, and suggested that documenting design changes would be helpful.

School B students also worked individually over the course of two weeks. However, these 7th grade students (ages 12-13), worked under the guidance of three science teacher and one instructional coach whose role was to facilitate coordination of the design project. These students worked on the design task in block scheduling, meaning their class length was approximately 90 minutes but met every other day. The teachers averaged over 14 years of experience teaching science, and averaged 1 year of experience in implementing engineering design projects. Three Purdue researchers introduced Energy3D in a live format and provided an overview of the design challenge in three separate computer labs to groups of approximately 30 students in a 30-minute shortened class period over the course of one day (See Figure 4).

School A is located within the same affluent, resource-rich, suburban town as School B. At School A, students worked in groups of four to five students and spent a total of 45 hours over a month under the guidance of three science teachers, three mathematics teachers, and one
instructional coach. School A also utilizes block scheduling, replacing a more traditional 40-50-minute daily subject class with longer 90-minute classes of each subject that meet fewer times each day and week. Teachers at both schools had common planning times, allowing full collaboration among teachers. In addition to the combined science and mathematics setting, the design project at School A differed from the design project common to Schools B and C in that a local homebuilder provided the challenge to design a home for his company to build in their town (M. Goldstein, Loy, & Purzer, 2017). Because of the different scale of implementation and different design challenge in School A, this school was only use in one phase of the study.

Teachers at all three schools encouraged students to take reflective notes within Energy3D during their design process to document their design changes and any associated analysis and results of those changes. In order to incentivize students, teachers shared that the “top” designs from the grade level would compete for a chance to have a design review and celebration with Purdue graduate students and prizes. At the completion of the two-week design challenges, teachers from all classes selected the top fifteen students. Teachers selected the “top” based on
their assessment of how well the student addressed the design challenge, overall effort, and ability to present to a large group. These students printed their final 2D design from Energy3D, cut out the pieces, and then assembled the pieces as a physical model of their home. They also prepared a PowerPoint slide of their home that detailed: (1) The name of their house, (2) area of house, (3) total construction cost, (4) special features, and (5) thoughts/reflection on the overall project. Students presented this information in an assembly to their peers prior to a more intimate design review with three Purdue researchers (See Figure 5). The overall time for both projects at School B and C is shown in Figure 6. A summary of the key implementation characteristics at all schools is provided in Table 3.

Figure 5. School B top designers with Purdue design review team

Figure 6. Timeline of design project and data collection at Schools A & C
Table 3. Key implementation characteristics summary

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>School A</th>
<th>School B</th>
<th>School C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resources</strong></td>
<td>Dedicated computer lab, available instructional videos</td>
<td>Dedicated computer lab, available instructional videos</td>
<td>Computers on loan from Purdue, available instructional videos</td>
</tr>
<tr>
<td><strong>Nature of experience</strong></td>
<td>Block-schedule, 4-week duration, separate design challenge, team-based</td>
<td>Block-schedule, 2-week duration in science class</td>
<td>50-min classes, 2-week duration in science class</td>
</tr>
<tr>
<td><strong>Students</strong></td>
<td>7th Grade students</td>
<td>7th Grade students</td>
<td>8th Grade students</td>
</tr>
</tbody>
</table>

**Data sources**

Data for this dissertation was collected during the Spring semesters in 2016 and 2017. Data collection at each school was conducted over approximately two weeks as part of an in-class design challenge. Data collected included: process data from Energy3D, a final design artifact from Energy3D, student design rationales elicited with an open-ended problem, and data collected with the Conceptions of Design Test (CDT).

**Process data**

As students designed their buildings in Energy3D, each student operation was recorded in the background of the program in JSON files called log data or process data. These operations, such as construction activities (e.g. add wall, edit wall, edit window, add tree, etc.), revisions (e.g. remove, move, rotate, etc.), analyses (i.e. run annual energy analysis), simulations (e.g. show heliodon, animate sun, show shadow, etc.), and documentation or reflection activities along with a timestamp of the operation allow a full reconstruction of each student’s design activity. Table 4 details the full schema of these design actions. In addition to these activities, design specifics for the final design (e.g. cost, dimensions, energy consumption) are were collected within the Energy3D platform. Per student, this log data sums 4,000 to 6,000 actions that provide a time-stamped catalogue to reconstruct the student’s design process.
Table 4. Energy3D action schema

<table>
<thead>
<tr>
<th>Categories</th>
<th>Summary of Included Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>Move/Rotate/Remove Building, Add Components</td>
</tr>
<tr>
<td>Door</td>
<td>Add/Edit/Remove Door</td>
</tr>
<tr>
<td>Floor</td>
<td>Add/Edit/Remove Floor</td>
</tr>
<tr>
<td>Foundation</td>
<td>Add/Edit/Paste/Remove Foundation</td>
</tr>
<tr>
<td>Roof</td>
<td>Add/Edit/Remove Different types of Roof, Convert to Gable, Resize overhang</td>
</tr>
<tr>
<td>Wall</td>
<td>Add/Edit/Remove Wall, Change Type of Wall</td>
</tr>
<tr>
<td>Window</td>
<td>Add/Edit/Paste/Remove Window</td>
</tr>
<tr>
<td>Façade</td>
<td>Color Change for House Components, Texture Change</td>
</tr>
<tr>
<td>Human</td>
<td>Add/Edit/Paste/Remove Human</td>
</tr>
<tr>
<td>Numeric Analysis</td>
<td>Daily/Annual Analysis, Remove or Show past data curves</td>
</tr>
<tr>
<td>Sensor</td>
<td>Add/Edit/Remove Sensor</td>
</tr>
<tr>
<td>Tree</td>
<td>Add/Edit/Paste/Remove Tree</td>
</tr>
<tr>
<td>Visual Analysis</td>
<td>Heliodon, Animate Sun, Shadow, Daily Cumulative Radiation</td>
</tr>
<tr>
<td>Insulation</td>
<td>Change Solar Heat Gain Coefficient, Change U-Value</td>
</tr>
</tbody>
</table>

**Design artifacts**

Students saved final versions of their home design in Energy3D. These files were opened in Energy3D to view the aesthetics of the final design, and run analyses to find 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 design criteria and constraints. Students were encouraged to create three iterations of their design, and were free to choose when to start working on one design or another, and were prompted to discuss which of their design iterations they deemed “best.” Final designs can be printed out as images of 3D models as shown in Figure 7. Here, the models show the final design from two perspectives (front and back) and a summary of performance (energy consumption, cost, window to wall ratio, etc.).
Student design rationale

Prior to and after completing their design project, students completed an open-ended performance task that asked them to explain their rationale for selecting one design solution from a set of three alternatives provided. Only the post-test was used in work for this dissertation because this work seeks to understand student variation rather than student change. As shown in Figure 8, the three alternatives are summarized in terms of different performance parameters similar to what was asked in Energy3D. Also, each alternative has strengths and weaknesses such that there is no obvious choice or single “correct” solution among the alternatives. The purpose of the performance task is to assess the extent to which students considered multiple trade-off factors when making a design decision in ways that are similar to their recent Energy3D project (See Table 5).
Table 5. The trade-off factors associated with building data

<table>
<thead>
<tr>
<th>Trade-Offs Factors</th>
<th>Building Information Given</th>
</tr>
</thead>
</table>
| Technical          | • Total annual energy consumption  
                     | • Approximate volume of building |
| Human              | • Total area of windows surface and walls  
                     | • Number of trees |
| Economic           | • Total construction costs  
                     | • Approximate volume of building |

The engineer in this situation needs to balance trade-offs between energy and cost while making sure enough light enters the building. Students have the potential to make connections between the benefits and the trade-offs from differing factors between the buildings (See Figure 8).

An engineer is asked to determine the best option among three buildings. She needs to balance trade-offs between energy and cost while making sure enough light enters the building through windows.

<table>
<thead>
<tr>
<th></th>
<th>Building 1</th>
<th>Building 2</th>
<th>Building 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Net Energy Consumption (kWh)</td>
<td>-1,000</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Total Material Cost ($)</td>
<td>59,626</td>
<td>55,000</td>
<td>49,000</td>
</tr>
<tr>
<td>Volume (m$^3$)</td>
<td>160</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Number of Trees</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Total Wall Surface (m$^2$)</td>
<td>185</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Total Window Surface (m$^2$)</td>
<td>16</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

Using the information provided above, which building would you suggest the engineer selects?

a) Building 1  
b) Building 2  
c) Building 3

Please explain your choice:

---

Figure 8. The open-ended design rationale question students used in pre and post-test
Conceptions of Design Test (CDT)

Students completed pre- and post-tests as part of their design experience. The Conceptions of Design Test (CDT) was used to characterize changes in learners’ prioritization and understanding of 20 design activities from “analyzing data” to “using creativity” (see Figure 9). The CDT was adapted from an instrument designed by Newstetter and McCracken (Newstetter & McCracken, 2001) and modified by Mosberg, et al., (Mosborg, Adams, Kim, Atman, & Cardella, 2005) to understand practicing designers’ design language. Later revisions of the tool focused on college designers’ conceptions of design (Adams & Fralick, 2010; Atman, Kilgore, & Mckenna, 2008; Cardella, Atman, Turns, & Adams, 2008).

Middle school and high school educators in previous data collections, 2015-2016, provided feedback as to which CDT terms would not be age-appropriate for their students, which contributed to a revised version for use in pre-college contexts. A large pilot study in spring 2016 (described in more detail in Chapter 2) looked at students’ overall understanding of terms and resulted in providing additional explanation in parentheses to five of the total terms. For example, “iterating” became “iterating (making revisions)”. This current version of the CDT is shown in Figure 9.

All students took the pretest 3-5 days prior to beginning the design activity and the posttest within a week after the completing the design project. The teacher administrated the tests during class sessions through Purdue Qualtrics, a web-based survey collection software tool.

The instrument in this current study of middle school students included four questions: Given the list in Figure 9 (in alphabetical order to reduce response bias) (1) “Select the five most important concepts for producing a high quality design”, (2) “For one of the five terms you marked as most important for producing a high quality, please explain why you believe it is important.” (3) “Select the five least important concepts for producing a high quality design”, and (4) “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.”
<table>
<thead>
<tr>
<th>List of Design Activities</th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Analyzing data</td>
<td>Selection: Which 5 would you consider MOST / LEAST important in terms of producing a high quality design?</td>
</tr>
<tr>
<td>• Balancing trade-offs (considering strengths &amp; weaknesses)</td>
<td>Open-ended response: For one of the MOST/LEAST important terms selected, please explain why</td>
</tr>
<tr>
<td>• Brainstorming</td>
<td></td>
</tr>
<tr>
<td>• Building</td>
<td></td>
</tr>
<tr>
<td>• Communicating</td>
<td></td>
</tr>
<tr>
<td>• Conducting tests</td>
<td></td>
</tr>
<tr>
<td>• Evaluating</td>
<td></td>
</tr>
<tr>
<td>• Gathering information</td>
<td></td>
</tr>
<tr>
<td>• Generating alternatives</td>
<td></td>
</tr>
<tr>
<td>• Identifying constraints (identifying limitations)</td>
<td></td>
</tr>
<tr>
<td>• Iterating (making updates)</td>
<td></td>
</tr>
<tr>
<td>• Making decisions</td>
<td></td>
</tr>
<tr>
<td>• Modeling</td>
<td></td>
</tr>
<tr>
<td>• Planning</td>
<td></td>
</tr>
<tr>
<td>• Prototyping (creating a test version)</td>
<td></td>
</tr>
<tr>
<td>• Reflecting</td>
<td></td>
</tr>
<tr>
<td>• Setting goals</td>
<td></td>
</tr>
<tr>
<td>• Sketching (using paper, computer, etc.)</td>
<td></td>
</tr>
<tr>
<td>• Understanding the problem</td>
<td></td>
</tr>
<tr>
<td>• Using creativity</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9. Conceptions of Design Test (CDT)

**Chapter Organization**

This dissertation is composed of three inter-related research studies. Summarized in Figure 10, these studies are designed to contribute to learning theories associated with design trade-off decisions made by pre-engineering student designers. These studies address the following research question:

1. What are middle school students' conceptual understanding of trade-offs in design?
2. How do students perform trade-offs in design and how can this performance be measured in a systematic, easy way that encompasses multiple competing and conflicting criteria and reflects competent design?
3. How do students dually perform and explain design trade-off decisions?
In this dissertation, I approach each of these objectives through distinct research questions and accompanying methodological frameworks. Chapter 2 seeks to understand student conceptions of making design tradeoffs through two parts: a statistical analysis showing how students conceptions change over the course of a design project, and qualitative description of their overall understanding of the importance of trade-offs. A version of this chapter was recently published in the *International Journal of Engineering Education*. Chapter 3 seeks to provide a Trade-off Value (TOV) protocol to measure design artifact quality that: (1) encompasses multiple complementary and competing dimensions, (2) can be applied consistently and systematically, and (3) is indicative of design. This protocol is then applied to student artifacts generated through Energy3D to explore patterns of student (“beginning designer”) trade-off behavior. Chapter 4 investigates student rationale associated with a design task, and through a cluster analysis builds a theory towards the different ways students experience and analyze design trade-offs. Finally, Chapter 5 provides a summative look at student trade-offs by weaving results from all three studies together.

The research of making sense of trade-off behaviors in student designers runs parallel to the process of sense-making in engineering, where engineers “seek coherence and meaning across multiple representations and sources of knowledge” (Danielak, Gupta, & Elby, 2014, p. 11). People make meaning of the world using multiple resources such as actions, visuals, spoken...
language, written language, and others (Bezemer & Jewitt, 2010). A multimodality approach assumes that representation and communication draw on multiple modes (Bezemer & Jewitt, 2010). Thus, using a multimodal approach in order to represent trade-off decisions in the student designer will result in a sense-making that is more fully articulated through interwoven meanings of these multiple modes of data. These three studies represent a multimodal approach in analysis and discussion of quantitative and qualitative data from multiple sources. This approach is important to make sense of trade-offs in students from a dual perspective of how students enact and critique trade-offs.

**Contribution**

This research is impactful in advancing theory that can help to prepare engineers with exceptional decision-making skills. In addition, the approach is creative and original because it proposes using learning analytics, an emerging area of research (Macfadyen, Dawson, Pardo, & Gašević, 2014), with more conventional data (e.g. tests and reflections) allowing a more comprehensive picture of the student design process. This comprehensive understanding provides the foundation on which to shape practices towards a goal of better prepared engineers. Furthermore, this work suggests a new yet comprehensive method for assessing design quality – as a score of balancing benefits and trade-offs.

There are few studies on how students are taught to make engineering design decisions (Jonassen, 2012), let alone the specific subset of trade-off decisions in a K-12 setting. Prior studies on K-12 student decision-making have examined decisions involving socio-scientific contexts. These studies have used qualitative methods such as ethnography (Brotman, Mensah, & Lesko, 2010), verbal protocol analysis (Schkade & Payne, 1994) and content analysis (Papadouris, 2012a). A study Mentzer, Becker, & Sutton (2015) investigated the time high school freshmen and seniors dedicated to design behaviors including decision-making high during in a playground design task through verbal protocol analysis. Due to the nature of the research methodologies, prior studies typically explore small numbers of cases, limiting the ability to examine variation. This project will include a larger sample size than can traditionally be included in a study of student design behaviors. Characterizing student trade-off decisions in student designers will improve our understanding of how and to what extent students engage in decision-making behaviors while designing. Furthermore, this knowledge could provide the foundational theory to allow K-12
educators to create appropriate design learning activities that build student decision-making abilities helping to prepare proficient engineers. Using engineering design activities that require an analytical approach to benefits and trade-offs provides a more comprehensive approach to engineering and might appeal to a greater range of students, encouraging a broader participation in engineering at the college level. However, more than preparing future engineering students, understanding trade-off decisions could benefit students on a larger scale by igniting critical decision-making in their roles as consumers and as citizens.
CHAPTER 2. UNDERSTANDING MIDDLE SCHOOL STUDENTS’ CONCEPTIONS OF TRADE-OFFS IN DESIGN


**Abstract**

Engineering design is a complex experience for students to undertake and for instructors to assess. Making trade-offs is an effective design practice, and is a key performance dimension in student design. However, research on K-12 students’ conceptions on 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 changes. In particular, this work addresses students’ use and prioritization of the term “balancing trade-offs” in design through the following research questions: (1) How do students’ prioritizing of “balancing trade-offs” change after introduction of a design activity, 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; trade-offs, design decisions, assessment, design conception
Introduction

Although design and decision-making are intertwined for practicing engineers, students from elementary school through college and graduate school are not taught to think through situations in which information is limited and goals are ambitious (R. Howard, 2007). In the design context, decision-making is defined as the interaction of information, alternatives, and preferences among alternatives involved in (Dym, Agogino, Eris, Frey, & Leifer, 2005; Papadouris, 2012b; Svarovsky, 2011) all stages of solving ill-defined problem (Crismond & Adams, 2012; S. Purzer, Duncan-Wiles, & Strobel, 2013). 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 (Otto & Antonsson, 1991). Although much is understood about professional designers’ behaviors as compared to novice designers and students, there is little research regarding student trade-off decisions while designing. Making trade-off decisions is an effective design practice, and is a key performance dimension in design (Crismond & Adams, 2012). 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 from problem solving skills and contribution to society. Grade school children have been studied making tradeoffs in design between cost and effectiveness (Purzer et al., 2013) and high school students were found to make science connections while taking part in an engineering design project while making tradeoffs such as energy performance in different seasons (Purzer, Goldstein, Adams, Xie, & Nourian, 2015). Working on developing these core engineering concepts gradually would allow students more developed design thinking ability.

Understanding how students value and reassess value of design strategies 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:

1 Copyright permission from IJEE included in Appendix D
RQ1. How do students’ perceived importance of “balancing trade-offs” change after introduction of a design activity?

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

Literature review

Engineering design

Some claim design as the distinguishing activity of engineering (Bucciarelli, 2003; Dym, 1994). 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” (Dym et al., 2005). 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” (Bucciarelli, 2003). 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 is the 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).

Because design is so critical to the engineering profession, it is a core focus in engineering education at the college level (Atman, Eris, McDonnell, Cardella, & Borgford-Parnell, 2014). In the United States, design has been explicitly recognized as a crucial component of an engineering education through accreditation criteria (ABET Accreditation Board for Engineering and Technology, 2014). 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” (ABET Accreditation Board for Engineering and Technology, 2014).

Additionally, engineering education at the P-12 level commonly suggests design is an appropriate pedagogical approach as seen in the Next Generation Science Standards (NGSS) (Achieve, 2013). Because of the focus on design through 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 P-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 inform better design education for these students and could allow more targeted education for university engineering students.

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 (Otto & Antonsson, 1991). 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 (National Research Council, 2001) 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” (National Research Council, 2001).

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 (Thurston, 1994) 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 (Quirante, Sebastian, & Ledoux, 2012) 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 when designers must consider trade-offs between performance, adaptability, and production costs (Mueller, 2011).

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 (2012), 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 ability to justify these decisions. Informed engineering designers are skilled at “weighing and articulating” (Crismond & Adams, 2012) 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” (Crismond & Adams, 2012). 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 suggested the importance of making trade-offs for these engineers. In one such study, Jonassen, Strobel, & Lee (D. Jonassen et al., 2006), 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 (Strobel & Pan, 2010), 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 next section, we discuss Asimow’s (1962) definition of design, which highlights the technical, human, and economic factors engineers balance in their workplace trade-off decisions. (M. H. Goldstein, Omar, Purzer, & Adams, 2018)
Conceptual framework

The conceptual framework for this study is based on Asimow’s (Asimow, 1962) characterization of balancing trade-offs as the interaction among competing factors to achieve high-quality designs. As shown in Figure 11, 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” (Asimow, 1962).

![Figure 11. Trade-off value conceptual framework](image)

Here, human refers to more than ergonomics by encompassing what humans want. Technical factors refer to design performance, often achieved through science and math concepts. Economic factors refer to monetary costs. Using a conceptual framework of trade-offs in design, (Asimow, 1962) 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 tradeoff 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 as the IDEO model of human-centered design emphasizing the intersection of desirability, feasibility, and viability (Brown, 2009) for innovation.

Methods

This paper presents addresses students’ use and prioritize the term “balancing trade-offs” in design through the following research questions: (1) How 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.

Participants & Design challenge

This research took place in three separate middle schools, with over 700 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. The large number of students form a diverse population sample. 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” (Nourian & Xie, 2016). 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 Figure 12).
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.

**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 6). The instrument included three sets of questions: (a) given the list in Table 6 (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.”

<table>
<thead>
<tr>
<th>List of Design Activities</th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analyzing data</strong></td>
<td><strong>Selection</strong>: Which 5 would you consider the MOST/LEAST important in terms of producing a high quality design</td>
</tr>
<tr>
<td><strong>Balancing trade-offs</strong></td>
<td><strong>Open-ended response</strong>: For one of the most/least important terms selected, please explain why</td>
</tr>
<tr>
<td><strong>Brainstorming</strong></td>
<td><strong>Building</strong></td>
</tr>
<tr>
<td><strong>Communicating</strong></td>
<td><strong>Conducting tests</strong></td>
</tr>
<tr>
<td><strong>Evaluating</strong></td>
<td><strong>Communicating</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Iterating</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Making</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Constraints</strong></td>
</tr>
<tr>
<td>Gathering</td>
<td>Planning</td>
</tr>
<tr>
<td>Planning</td>
<td>Prototyping</td>
</tr>
<tr>
<td>Information</td>
<td>Reflecting</td>
</tr>
<tr>
<td>Alternatives</td>
<td>Setting goals</td>
</tr>
<tr>
<td>Identifying</td>
<td>Sketching</td>
</tr>
<tr>
<td>Constraints</td>
<td>Understanding the problem</td>
</tr>
<tr>
<td>Iterating</td>
<td>Using creativity</td>
</tr>
<tr>
<td>Making</td>
<td>Modelizing</td>
</tr>
</tbody>
</table>
| Open-ended response: For one of the most/least important terms selected, please explain why
Data analysis

Quantitative Analysis

To understand (RQ1) how students’ perceived importance of “balancing trade-offs” change after introduction of a design activity, we conducted a McNemar test for:

1) Pre- to post-test responses to the CDT “Which 5 would you consider the MOST important in terms of producing a high quality design?” for “balancing tradeoffs”
2) Pre- to post-test responses to the CDT “Which 5 would you consider the LEAST important in terms of producing a high quality design?” for “balancing tradeoffs”

McNemar’s tests were performed to determine whether proportions of “balancing tradeoffs” 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 (Sheskin, 2004). This test provided a statistical measure of change in priority of “balancing trade-offs”.

Qualitative Analysis

In order to understand (RQ2) how students’ conceptions of “balancing trade-offs” change after introduction of a design activity, we performed a qualitative analysis of students’ responses to the open-ended question, “For one of the five terms you marked as most/least important for producing a high quality design, please explain why you believe it is/is not important.” We only reviewed instances when students described “balancing trade-offs.” Please note that since students only 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 7.

Table 7. Frequency with which “balancing trade-offs” is described in open-ended responses

<table>
<thead>
<tr>
<th>Test</th>
<th>IS Important</th>
<th>IS NOT Important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-</td>
<td>1</td>
<td>42</td>
</tr>
<tr>
<td>Post-</td>
<td>3</td>
<td>20</td>
</tr>
</tbody>
</table>
We performed a content analysis to systematically categorize students’ open-ended responses to describing balancing trade-offs in engineering design (Patton, 2005). The analysis was iterative, moving from inductive to deductive states so that themes would emerge from the data (Patton, 2005). In this systematic characterization, the researchers identified the unit of analysis to be the 66 responses that specifically address balancing trade-offs. With only 66 student responses, students tended to respond in one of four ways or codes: (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.

Results & Discussion

Previous design research with secondary students’ found that opportunities for meaningful science learning through engineering design occurred when students attempted to balance benefits and trade-offs (Purzer et al., 2015). Based on this research and previous research with the CDT (Adams & Fralick, 2010), we are assuming that (1) asking students about their priorities allows us to get to an understanding of their reasoning, and (2) that young adults can explain their rationale in writing. While we are attempting to understand student conceptions of design, their brief open-ended responses will not provide a rich description but rather a starting point for understanding. While other methods such as student interviews and think aloud protocols would allow a different perspective on students’ understanding of language, this approach is pragmatic with our middle school population.

How do students’ perceived importance of “balancing trade-offs” change after introduction of a design activity?

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

A 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, \( \chi^2 = (1, N= 746) = 6.33, p = .01 \), but not as a MOST important terms, \( \chi^2 = (1, N= \)
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.

Table 8. “Balancing trade-offs” change in priority from pre to post-test

<table>
<thead>
<tr>
<th>Shift in Importance</th>
<th>Pre Test (N, %)</th>
<th>Post Test (N, %)</th>
<th>P sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Important</td>
<td>More 32, 4.3%</td>
<td>41, 5.5%</td>
<td>0.30</td>
</tr>
<tr>
<td>Least Important</td>
<td>More 389, 52.1%</td>
<td>343, 46.0%</td>
<td>&lt;0.01*</td>
</tr>
</tbody>
</table>

**p<.05, ***p<.001

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

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. The 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.”

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 you 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.

Conclusions & future work

Although a statistically significant fewer number of students found “balancing trade-offs” to be unimportant to design quality from pre- to post-test, 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 in 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 tradeoffs, specifically using the language of tradeoffs.

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 tradeoffs” 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 tradeoffs 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 tradeoffs (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 tradeoffs (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.
Acknowledgments

We appreciate the data organization and analysis support from undergraduate research assistant, Sharifah Omar, as well as the collaboration from our colleagues, Charles Xie and Jie Chao, at the Concord Consortium. We are grateful for the students who participated in this study and for their teachers who supported data collection efforts. This work presented in this manuscript is based upon work supported by the National Science Foundation (NSF) under Grant DUE #1348547 and DUE #1348530. 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 NSF.
CHAPTER 3. A MEASURE OF DESIGN ARTIFACT QUALITY TO ENCOMPASS MULTIPLE DIMENSIONS: AN EMPIRICALLY-BASED METHOD

Abstract

Designers and design researchers have methods to assess design artifact quality. While useful, these methods are not necessarily easy to use nor do they indicate design competency. Moreover, they are not grounded in a definition of engineering design. The objective of this study was twofold. First, was to develop a protocol to depict 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. Second, was to test this Trade-off Value protocol to understand patterns of quality variation in students’ artifacts. Through a critical survey and comparison of current assessment methods in design quality I identify a gap for a tool to address assessment of competing and complementary design dimensions while encouraging effective design practices in student designers. I conceptualized a quantitative representation of the degree to which a design addresses human, technical, and economic requirements called the Trade-off Value protocol. I applied the Trade-off Value protocol to 398 middle school students who were designing energy efficient homes and used an etic approach to thematic analysis of the student design artifacts to understand the patterns of variation within this set of design artifacts. The Trade-off Value meets the three goals in assessing student designs, suggesting this protocol has value for understanding trade-offs in design artifacts. Second, I found five distinct patterns of variation in the set of student design artifacts which suggests patterns in ways students address design dimensions and indicates varying design competency. Trade-off Value is a useful method for three reasons. First, because it is conceptually grounded in the definition of design, it provides a comprehensive way to think about the interaction of client/user priorities, design possibilities and objective measures. Second, the protocol while being systematic is also easy to use. Third, the Trade-off Value protocol represents an important feature of design competency with which beginning designers struggle.

Keywords: decision making, design education, engineering design, trade-offs
Introduction & Motivation

It is difficult to assess student designs where the range of “correct” answers is wide. Within an engineering context, design is “a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints” (Dym et al., 2005, p. 104). Here, design involves attending to an interconnected system of non-negotiable (e.g., natural laws) and negotiable (e.g., social, political, economic, aesthetic, etc.) issues (Goel & Pirolli, 1992). The degree to which a designer addresses all dimensions of the interconnected system and the resulting performance of the design constitutes the overall quality of a delivered design solution.

A need to better understand design quality has been recognized globally from both the design community and stakeholders in design projects (Gann, Salter, & Whyte, 2003) stemming from the concern that a lack of balancing trade-offs by instead focusing on reducing cost and time on projects could lead to a “loss of functionality and boring, unattractive design” (Gann et al., 2003, p. 319). Gann and colleagues (2003) note that measuring overall design quality presents major conceptual and practical problems despite the clear need for designers and researchers to be able understand the overall effectiveness of a final design artifact. Similarly, Atman, Adams, Cardella, Turns, Mosberg & Saleem (2007) in comparing expert and novice designers’ solution quality are transparent in issues and difficulty of quality assessment. They point out how techniques such as “holistic judgments by panels of experts, instructors, peers, and combinations thereof to rubrics that operationalize the specific dimensions that are assumed to represent quality” (Atman et al., 2007, p. 363) will affect the resulting evaluation.

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

This paper addresses the need for a measurement of design quality that encompasses many dimensions of performance. Through the context of a design project directed towards a net-zero energy home using the Energy3D platform, I developed a protocol to calculate design quality that has characteristics of consistency and ease of use, a systems approach to addressing multiple dimensions, and a grounding in design competency. I then tested that protocol, the Trade-off Value protocol, in a middle school classroom with 398 students in order to determine if this method does in fact accomplish those three goals. Through the analysis of student cases, I identified meaningful variations in how students addressed multiple design dimensions and exhibited design competency.

**Guiding Question**

How can we depict 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?

**Conceptualizing a multidimensional idea of trade-off**

Engineering design includes 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 design performance (often through science and math 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 trade-offs.

Consider two different options of coffee machines: Mr. Coffee® and Technivorm Moccamaster®. A Mr. Coffee® coffee machine works by a user adding coffee grounds to a filter and filling the reservoir with water. Water from the reservoir flows through a hole into the heating element where the water boils and then flows to the drip area over the coffee grounds. The coffee flows into a container that sits on top of a heating element to keep the coffee warm. The key benefit of this machine is the low cost. However, the heating element can compromise the flavor of the coffee. Aesthetically, it is a standard and familiar style, which may make it easy to use. The
Technivorm Moccamaster® involves similar steps from the user of filling a filter with grounds and reservoir with water. This machine touts a 9-hole spray arm for an even soak of the beans prior to extraction for a fresh taste. Other technical features of this design include a quick and quiet brew time and ability to pour a cup of coffee mid-brew cycle. The hot plate has two settings that prevent coffee from scorching. Aesthetically, it is a modern and sleek design. However, the cost is ten times that of a standard Mr. Coffee®.

In choosing between these two coffee machines, a person might appreciate low cost of a coffee machine while another might feel that the other dimensions (technical and human) reduce the quality of a coffee experience. For the person who prefers the Mr. Coffee® machine, the positive aspect of the design, cost, might outweigh the negative aspects such as heating elements and their relationship to flavor (See Figure 13). In the second example, a person might value the sleek appearance (human dimension) of the Technivorm Moccamaster® in combination with technical dimension (evenly soaked beans, brew time, ability to pour mid-brew, etc.) more than they care about a lower cost (See Figure 14). Each of the two coffee machines have positive and negative aspects of their design, and trade-offs between the positive and negative contribute to the overall perceived value of the product.

Figure 13. Mr. Coffee® design trade-offs
The model of design quality discussed in this study, the Trade-off Value, characterizes this key issue of multiple complementary and competing values. As shown in Figure 15, Asimow’s (1962) characterization of the distinct dimensions or factors in engineering design is a guiding principle of this Trade-off Value which is 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 consideration paid to the competing dimensions rather than focusing solely on optimizing one or two of the dimensions. Figure 15 demonstrates the overlap of the dimensions as the Trade-off Value. This idea complements more current views such the IDEO model of human-centered design emphasizing the intersection of desirability, feasibility, and viability (Brown, 2009) for innovation. As the Trade-off Value framework is complementary to other existing frameworks, it may be broadly useful to designers and design educators.
Linking trade-offs to design competency

In this chapter, I discuss three variations in design experience: (1) “professionals,” or design experts with lots of experience, (2) “informed designers,” or those with a median competency that is an appropriate target for college, and (3) “beginning designers,” who are towards the naïve end of the spectrum in that they may have some design experience but may not understand key ideas. Beginning design students work to build their knowledge of design with a goal of developing into more able designers through their design experiences. Crismond & Adams’ (2012) *Informed Design Learning and Teaching Matrix*, based on a meta-literature review of more than 50 studies, synthesizes and describes key design behaviors that differentiate these beginning designers from competent designers ready to further their proficiency as they graduate school and enter the practice. One of these key dimensions of design performance and indication of design competency is making trade-offs (Crismond & Adams, 2012). Professionals think through the benefits and trade-offs of different design alternatives as a part of their design thinking and decision making (ITEA, 2000). Akin and Lin (1996) describe this as a process of “honeycombed” decisions (Akin & Lin, 1996). 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 alternatives for material alone the design team needed to consider weight, corrosive resistance, flexibility, and manufacturing options. Moreover, practicing designers work through complex and ill-structured problems that require both weighing options and forecasting the impact of these decisions (Strobel & Pan, 2010).

Design also includes making 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 of design trade-offs. 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.

On the other end of the spectrum, beginning designers do not have the same understanding of design as experts or informed designers in many areas of design including making design trade-off decisions. In summarizing studies of beginning designers Crismond and Adams (2012) emphasize that beginning designers do not 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). Moreover, when describing a design decision, they are apt to cite only a pro to the chosen design or a con of a passed over design (Crismond & Adams, 2012) such as referencing high cost as a negative aspect of a design or energy efficiency as a positive aspect. Because making trade-offs is such a key design activity of practicing engineers, design artifacts that indicate students have acted like an informed designer and have made trade-offs might suggest a level of design competency.

**Examining approaches to measuring quality that guide the trade-off value protocol**

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

**Designer tools to assess design artifact quality**

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

One design tool, *A quality loss approach* (Akao, 1990; Hauser & Clausing, 1988) to assessing design quality, particularly in assessing groups of design ideas during ideation and iteration cycles, is used in design practice and design education, as well as design research. In fact, using this tool in design began with Mitsubishi in the 1970s (Hauser & Clausing, 1988). There are a variety of quality loss approaches, such as Taguchi methods, Quality Function Deployment (QFD), and House of Quality. Each offers a systematic and organized approach to make clear the
relationships between manufacturing functions and customer satisfaction in an easy to visualize manner. These performance goals are not prescribed within the tool, and those who use these tools often identify issues that span technical, economic, and human dimensions. To use this approach, performance goals are represented in a matrix form that lists each customer requirement that will be rated (often on a scale of 1-5) as the “whats” and each technical requirement that will be rated similarly as the “hows” (See Figure 16 for an example). Then, qualitative comparisons across multiple and potentially competing technical performance and customer attributes can be made. When using these tools during the ideation phase of design, the focus is often on comparing a set of alternatives to choose an option (or combination of options) that has the most promise. For use during iterative improvement cycles, the focus is often on ways to monitor and optimize solution performance (e.g., pointers to examples). Overall, the premise of a quality loss approach asserts that “good” design is robust and less sensitive to uncontrollable factors in both manufacturing and use (Otto, 1995). The “quality score” produced is a numerical representation of how well a solution meets customer priorities and engineering specifications in relation to other design options.
Another designer tool features a mathematically-grounded approach to assessing the quality of a design concept, *Axiomatic Design* (Suh, 1990). This method is often used in assessing designs at the ideation and “optimization” or iteration phase. The premise of this framework is the relationship between the customer domain (CAs), functional domain (FRs), physical domain (DPs)
and process domain (PVs) (See Figure 17). In Axiomatic Design Theory, a designer should strive to maintain the independence of the functional requirements while minimizing the information content of the design, where information content is related to the probability of success of a particular FR and DP design concept. A key strength of using this approach to assess a design is that it allows a systems perspective, with sets of interrelated criteria in a repeatable manner. However, this predominantly conceptual approach is difficult to use and interpret, especially in more complex design situations (Suh, 1990). This approach does not result in a final score or overall ranking of design alternatives, but instead can identify internal technical conflicts.

![Figure 17. Axiomatic Design depiction (adapted from Suh, 1990)](image)

A third tool used by both designers in practice and student designers are *Decision Matrices* (e.g. Pugh Decision Matrices (Pugh, 1990)), which make risks in design alternatives visible by explicitly comparing strengths and weaknesses between designs. While this tool can be used at any stage of the design process, it is typically employed at the ideation stage. The designer will develop a list of criteria and assigns a score to each criterion of each alternatives. An important distinction for Decision Matrices as opposed to QFD and House of Quality approaches is that there are no weightings of criteria as this method is based on simple ratings (e.g., yes/no/maybe) or comparative ratings (e.g., better than the other options, same, or worse). Categories for evaluation are not pre-defined in this tool, but typically include effectiveness, feasibility, capability, cost, and time. This tool allows evaluation and prioritizing a list of options through a numerical, ordinal representation from a group of designs or options.
A final approach to be discussed, *metrics for measuring ideal effectiveness* (Shah, Vargas-Hernandez, & Smith, 2003), is meant to assess ideation effectiveness through the following subscores: quantity, quality, novelty and variety within a set of ideas. It is typically used for evaluation of groups of ideas. Quality is seen as an estimated measure of the degree to which a design idea met design specifications and was feasible. This broad view of quality refers specifically to conceptual and was not developed to assess final design solution quality. In determining quality, one particular design has to serve as the baseline comparison for other designs. This can make the measurement approximate and cognitively difficult.

Each of these methodological approaches for assessing design quality are typically employed at the ideation stage or conceptual design. As such, they can provide early insights into how a design solution may perform or underperform that can be addressed through iterative cycles. Therefore, these approaches can be effective formative assessments for students, providing feedback as students progress through the design process. A strength of these methods is that they provide a framework to explicitly make both benefits and risks (or advantages and disadvantages) of the design visible to the design decision-maker. Although these approaches are generally classified as designer tools, the extent to which each is used within design education varies. In a review of fourteen commonly used engineering design textbooks used in first-year engineering, Purzer and Chen (2010) found that tools to assist in understanding design quality, specifically for decision-making, are mentioned only briefly or as an ancillary step in the design process in half of the textbooks. In reviewing five of the cited textbooks from their study (Brockman, 2009; Dieter & Schmidt, 2009; Dym, Little, Orwin, & Spjut, 2009; Niku, 2009; Oakes, Leone, & Gunn, 2006) plus an additional two influential texts (Cross, 2008; Pugh, 1990), I found *decision matrices* and *quality loss approaches* (House of Quality) are explicitly referenced as design tools.

Table 9 summarizes these designer tools used to assess design across dimensions of: (1) ability to reflect multiple complementary and competing dimensions with an explicit focus in referencing Asimow’s (1962) three areas of technical, human, and economic trade-offs, (2) application consistency, (3) ease of use, (4) design phase used in, (5) tool audience (designer or researcher), (6) indicative of design competency, and (7) use of method in design education.
<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Quality loss</th>
<th>Axiomatic design</th>
<th>Pugh decision matrices</th>
<th>Metrics for measuring ideation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Addresses multiple complementary &amp; competing dimensions (RQ1):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Technical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Human</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Economic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Applied consistently (RQ2)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Indicative of design competency (RQ3)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Easy to use</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Applicability in different settings/generalizable</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Design phase:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Ideation or Optimization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Final/Prototype</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Formative assessment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Summative assessment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tool audience:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Designer tool</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Researcher tool</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Used in design education</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Key:**  ● = yes,  ○ = no,  □ = sometimes
All of the designer tools to assess quality in Table 9 address multiple complementary and competing dimensions, although none of them necessarily prescribe human, technical and economic dimensions. A common strength across all approaches is that they are systematic, but a common weakness is that they may not be easy to use. All approaches can be useful in the ideation and optimization phases, and can be useful in providing feedback to the designer, so they have potential utility as a formative assessment. Decision matrices and decision analysis methods can also be used in final artifacts and have some utility as summative assessments. Collectively, all of these types of tools allow comparisons of design ideas or solutions in a visual way. However, it is only through the use of these tools that we can get a sense of student design competency.

**Design researcher tools to assess design artifact quality**

In design research literature, the role of a quality score for student design outcomes is often used to explore correlations between outcomes and design processes or behaviors (Atman et al., 2007; Atman, Cardella, Turns, & Adams, 2005; Atman, Kilgore, & McKenna, 2008; Cardella, Atman, Turns, & Adams, 2008, Yang, 2003, 2005, 2009). These key empirical studies utilize an expert judge or set of scorers to determine a quantitative quality score for a design artifact. The following sections detail two types of quality assessments: assessment of the design solution itself and assessment of design documents through research papers that illustrate these assessment types. In both types of design researcher assessments, the researchers use a rubric to evaluate the solution or documentation, and follow a procedure to convert the qualitative solution/documentation to a quantitative measure. Oftentimes, there is an explicit effort to calibrate scores through interrater reliability in these types.

Researcher evaluation tools to assess design solutions can be systematic, especially with documented and well-understood rubrics. One such systematic approach used a detailed rubric to assess the quality of final design solutions to address a playground challenge in several studies with undergraduate engineering students and experts (Atman et al., 2007; Atman, Cardella, Turns, & Adams, 2005; Atman, Kilgore, & McKenna, 2008; Cardella, Atman, Turns, & Adams, 2008). In these studies, the research team served as expert judges, following the rubric and ranking each design. They made pairwise comparisons between all possible pairs of design solutions and assessed inter-grader reliability for consistent scoring. A constant sum algorithm, a scaling
technique that involves the assignment of a fixed number of units to each rubric element, was applied to arrive at the set of relative weights, and to be normalized to a score of one. The rubric addressed each design’s ability to meet design criteria explicitly specific to the design task (playground). Because this comprehensive rubric included playground principles such as safety standards for particular playground equipment, it is not a generalizable rubric. The final score, “quality of design solution score” represented how well students addressed design criteria and this score was correlated with other measures of undergraduate engineering student design processes.

Another type of research focuses on the assessment of design documents. In one such study, Dong and colleagues (2004) calculated what they termed an “outcome quality” of final solutions as described in written reports from teams of graduate students in their “document analysis method for characterizing design team performance” (Dong, Hill, & Agogino, 2004). Two researchers used a rubric to evaluate the designs. The rubric consisted of 13 categories, including mission statement, user scenarios, customer and user needs, and concept sketches. Researchers assigned a score of 1 (worst) to 5 (best) to each category, resulting in a final ordinal ranking. This final ranking of design outcome was used for further statistical analysis to correlate design quality with levels of semantic coherence in design documents.

A third type of research focuses on the assessment of design solutions and design outcomes. In an example of this time of assessment, Yang (2003, 2005, 2009) studied undergraduate engineering students and measured “design outcome” as quality of a final design solution as a prototype in two ways (Yang, 2003, 2005, 2009). The first method was an individual final grade, given based on class assignments and a design logbook. The second method was each team’s final ranking in the design contest, based on the number of rounds that the team was able to win. Design outcome score was used to perform statistical analysis with prototype characteristics such as level of simplicity and time spent making the prototype.
# Table 10. Summary of dimensions in researcher tools used to assess quality

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Playground Rubric by Atmen et</th>
<th>Document analysis method by</th>
<th>Yang prototype design</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Addresses multiple complementary &amp; competing dimensions (RQ1):</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Technical</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>-Human</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>-Economic</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><em>Applied consistently (RQ2)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Indicative of design competency (RQ3)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Easy to use</em></td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><em>Generalizable</em></td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><em>Design phase:</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Ideation or Optimization</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>-Final/Prototype</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><em>Formative assessment</em></td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><em>Summative assessment</em></td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><em>Tool audience:</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Designer tool</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>-Researcher tool</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><em>Used in design education</em></td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

**Key:** ○ = yes, ◯ = no, ○ = sometimes
Research methods to assess design quality do not explicitly indicate design competency but are often used to understand relationships or correlate with design competencies and behaviors. There are, however, limitations in research tools used to assess design. One such limitation is the understandable subjectivity in raters that could result in assessment due to personal philosophies and values, causing the experts to weigh certain elements differently (even when using a rubric, as experts likely have to balance trade-offs within the rubric). In addition, finding experts for a particular area and crediting them with “expert” status can be difficult. In general, because this group of assessment approaches requires a thorough review of the design and all associated data and design features, they are not easily scalable to large classrooms without the burden of excessive time.

Opportunity for a new perspective in measuring design quality

Despite the relevance and need for a measurement of design quality, it is easy to understand some of the limitations in current approaches of measuring quality of student design solutions. While all of these approaches address multiple dimensions, none explicitly are guided by Asimow’s depiction of human, technical, and economic dimensions. In addition, all of these methods can be applied consistently, but they vary drastically in ease of use from simple to overtly complex. Most importantly, with the exception of decision matrices, none of these methods are explicitly indicative of a design competency of balancing trade-offs.
Table 11 compares both designer and research tools to assess quality with the proposed Trade-off Value method presented in this paper. The Trade-off Value protocol was developed to address the gaps in current approaches to be a highly useful protocol.
Table 11. Summary of dimensions in designer & researcher tools used to assess quality

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Quality loss</th>
<th>Axiomatic design</th>
<th>Pugh decision matrices</th>
<th>Metrics for measuring ideation</th>
<th>Playground Rubric by Ammen et al.</th>
<th>Document analysis method by Dong et al.</th>
<th>Yang prototype design outcome</th>
<th>Trade-off Value Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addresses multiple complementary &amp; competing dimensions (RQ1):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Technical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Human</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Economic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied consistently (RQ2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indicative of design competency (RQ3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easy to use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applicability in different settings/generalizable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design phase:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Ideation or Optimization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Final/Prototype</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formative assessment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summative assessment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool audience:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Designer tool</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Researcher tool</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Used in design education</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key:  ● = yes,  ○ = no,  □ = sometimes

Trade-off Value Protocol

To understand the trade-offs students made during their designing, I conceptualized a quantitative representation of the degree to which a design artifact addressed human, technical, and economic requirements, building upon previous work in approaches to quality scores with a similar design challenge in Energy3D (Goldstein, Viera, Adams, Purzer, & Zielinski, 2016). A
quantitative representation was important in order to be able to easily and consistently assess student design artifact quality with the large dataset.

**Quality score pilot**

In the first iteration of developing a quality score within a larger NSF project, we reviewed a sample of 84 high school students’ design artifacts in Energy3D through three mathematical approaches and compared results to two experts’ evaluation of the same design artifacts (Goldstein et al., 2016). One of the approaches compared the *net-values* given by the simulations of Energy3D for each student to the extreme performances in the sample overall (e.g. maximum energy consumption, maximum cost). The second approach ranked a student’s design using *performance percentiles* to compare them to each other, and integrate the different criteria within the sample scale. Both approaches used the same data and therefore leveraged the “big data” affordances of Energy3D. The net-value approach involved weighting the relationship between performance dimensions while the percentile approach involved a mathematical normalization process within a given sample. Given the context of the design challenge, we included the following variables in the quality score calculation: annual net energy consumption, construction cost of house materials, livability, and number of unsatisfied constraints. In order to understand the fit of our approaches to expert evaluation, two researchers ranked the student design artifacts in terms of overall “quality.” These two expert judges were provided with single-page summaries for each design that included two pictures of the designed house and a table with the summary of the performance measures: annual energy consumption, cost, area, and volume of the house, number of trees, window area to wall area ratio, and whether the design satisfied each of the constraints. The two judges organized the student designs in different piles based on what they considered as high or low quality design artifacts. We created two sets of weighting coefficients for the net-value approach based on these piles, trying to get as close as possible to experts’ criteria. After computing the quality score using different weighting coefficients, we organized designs based on a 0-1 scale, where 1 corresponded to the best design and 0 corresponded to the worst one. This latter step was necessary in order to compare different approaches under the same scale. Results of the two approaches are discussed in more detail in Goldstein et al., 2016.
Pilot study lessons learned

The results from the pilot study suggested that different approaches and different weighting coefficients within the same approach would lead to different or even contradictory results. Although the weighting coefficients were “calibrated”, calibration is context-dependent, and involves a certain degree of subjectivity.

These studies indicate that taking an “overall” quality approach to evaluating a design solution did not resolve our early concerns regarding repeatability, subjectivity, and credibility. Even though we took a very systematic approach, the open-endedness of the tasks requires students to continually make trade-off decisions to find a balanced solution that meets the criteria. Each of the quality assessment approaches and weighting coefficients benefitted one of the design dimensions more than the other ones, and therefore, the results were found to be inconclusive.

Therefore, we revisited the expert review process used to generate weighting coefficients. In reflecting on their process, the expert judges (two researchers) noted they had some variations in their ratings dependent on what they found important. Rather than labeling this as “subjectivity”, we noticed that the considerations driving many of these ratings involved balancing trade-offs in the designs, even if the trade-offs were not explicit. For example, the judges tried to understand the relationship in overall quality between energy consumption and total cost. In some cases, this meant creating sub-piles of designs that did not meet one or more criteria (e.g., low energy consumption or total cost), but met other criteria including the more subjective criteria. We also noticed that the biggest factor contributing to livability for the judges was the presence of windows that would allow sunlight to enter the home; designs that had a “dungeon” quality with little sunlight received lower ratings. Similarly, designs that experimented with the overall shape of the house (beyond a four-wall square or rectangle) were likely to receive “bonus points”. In many cases, these “livability” issues provided a first step towards ranking designs, followed by an iterative approach of seeing the whole picture of how a design met (or didn’t meet) all the criteria. Additionally, the judges confirmed that the presence of trees did not impact final ratings, including assessments of overall aesthetics. It should be noted that most, if not all, designs included trees, and as such the details of tree placement did not substantively distinguish designs.
Trade-off Value approach

Building on the pilot study findings, I saw that the judges in evaluating student designers were taking an approach to understand the extent to which the artifact reflected a balance in conflicting objectives. To understand the trade-offs students were making I calculated a value for each human, technical, and economic feature of each student’s design, mapping to Asimow’s definition of engineering design as a “synthesis of technical, human, and economic factors.” (Asimow, 1962, p. 2). I mapped log data from Energy3D to the conceptual framework, as shown in Table 12. As shown here, some calculations (e.g., volume of home) map to multiple criteria, demonstrating system inter-relationships among size of the house, energy consumption, and total construction cost.

**Table 12. Trade-off framework with associated log data**

<table>
<thead>
<tr>
<th>Engineering Dimensions</th>
<th>Representative Design Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td>- Total annual energy consumption (energy/volume)</td>
</tr>
<tr>
<td></td>
<td>- Number of satisfied constraints (out of 8 so as to not “double count” cost)</td>
</tr>
<tr>
<td>Human</td>
<td>- Total area of all windows &amp; walls of home (e.g., “livability” as demonstrated through Window-to-wall ratio for house)</td>
</tr>
<tr>
<td>Economic</td>
<td>- Total construction costs (cost/volume)</td>
</tr>
</tbody>
</table>

Student performance within each of these trade-off dimensions are converted to percentile rank, ensuring that the rank order is logical 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 with 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.

\[
\text{Trade-off Value} = \sum_i \%\text{ilerank(Human factors)}_i + \sum_j \%\text{ilerank(Technical factors)}_j + \sum_k \%\text{ilerank(Economic factors)}_k
\]

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 this protocol is the ability to quantitatively assess student design performance within a set of designs in order to calculate each percentile ranking.

**Methods**

This empirical study based on a conceptual framework of trade-offs and design competency seeks to understand how we can depict design artifact quality that: (1) encompass multiple complementary and competing dimensions, (2) can be applied consistently and systematically, and (3) is indicative of design competency.

**Students and Design Challenge**

This study was conducted with 398 students at two middle schools (ages 12-14) in the Midwest, 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 with criteria and constraints shown in Table 13. 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 economical. This was an authentic problem-solving experience for students as it included multiple, conflicting goals with competing criteria (Jonassen, Strobel, & Lee, 2006).
Table 13. Design challenge criteria and constraints

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>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)</td>
<td>Cost cannot exceed $250,000 in building materials</td>
</tr>
<tr>
<td>Minimize total cost of the building</td>
<td>Each side of the house must have at least one window.</td>
</tr>
<tr>
<td>Comfortably fit a 4-person family (approximately 2200 ft$^2$ or 204 m$^2$)</td>
<td>Do NOT add more than 40 solar panels (regardless of their conversion efficiency).</td>
</tr>
<tr>
<td>Has an attractive exterior and is desirable</td>
<td>Keep the room temperature of the house to be 20°C all the time.</td>
</tr>
<tr>
<td></td>
<td>The house’s platform must not exceed the 28 x 36 m platform provided in the software.</td>
</tr>
<tr>
<td></td>
<td>Tree trunks must be outside house.</td>
</tr>
<tr>
<td></td>
<td>Only 1 structure on the platform (no doghouses, detached garages, etc.).</td>
</tr>
<tr>
<td></td>
<td>There is no need to design any interior structure such as rooms, floors, or stairs.</td>
</tr>
</tbody>
</table>

Students were instructed to create three distinct designs, and were free to choose when to start working on one design or another. The energy-efficient design challenge introduced at both schools involved using Energy 3D to design single-family homes. Students were instructed to create high quality home designs that attempted to balance energy consumption, construction cost, livability, and aesthetics. See Chapter 1 for additional contextual and implementation information.
Data sources and Collection

This research was conducted in large part through using a free, open-sourced computer-aided design platform, Energy3D (http://energy.concord.org/energy3d/), for students to design and build energy efficient buildings (see Chapter 1). This software is very user-friendly and was developed with educational research purposes in mind (Xie, Schimpf, Chao, Nourian, & Massicotte, 2018). As students design in Energy3D, a logger collects their process data behind the scenes (i.e., all user interactions with the software). In addition to fine-grained process data (such as edit window, add solar panel, etc.), Energy3D records design specifics for the final design. The following performance data was 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 eight. This data speaks to the three dimensions of the framework (shown in Table 14).

<table>
<thead>
<tr>
<th>Engineering Dimensions</th>
<th>Representative Design Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td>- Total annual energy consumption (energy/volume)</td>
</tr>
<tr>
<td></td>
<td>- Number of satisfied constraints (out of 8 so as to not “double count” cost)</td>
</tr>
<tr>
<td>Human</td>
<td>- Total area of all windows &amp; walls of home (e.g., “livability” as demonstrated through Window-to-wall ratio for house)</td>
</tr>
<tr>
<td>Economic</td>
<td>- Total construction costs (cost/volume)</td>
</tr>
</tbody>
</table>

Data analysis: Trade-off Value Protocol

Using the Trade-off Value Protocol, I calculated a quantitative representative of the degree to which a design addressed human, technical, and economic requirements. Table 14 summarizes how the log data, generated within the Energy3D system, were mapped to the Asimow (1962) characterization of engineering design. As shown here, some calculations (e.g., volume of home) map to multiple criteria, demonstrating system inter-relationships among size of the house, and the energy consumption, and total construction cost.
Applying the Trade-off Value Protocol to this particular design challenge within Energy3D involved making some decisions to best represent student design data. I 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. I represented livability of the house through a calculation of 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 14 (i.e., energy/volume, number of met constraints, window-wall ratio, and cost/volume) were converted to percentile rank within the population sample, ensuring that the rank order is logical in Equation 1 (e.g., a high construction cost/volume is undesirable and would result in a lower percentile rank while a high window to wall ratio is desirable and would result in a higher percentile rank).

Finally, the composite Trade-off Value for each student was calculated as the sum of the percentile ranks of: human dimensions, technical dimensions and economic dimensions, as shown in Equation 2, with a score range of 0-400.

\[
\text{Trade-off Value} = \sum_i \%\text{ilerank}\text{(Human factors)}_i + \sum_j \%\text{ilerank}\text{(Technical factors)}_j + \sum_k \%\text{ilerank}\text{(Economic factors)}_k
\]

Equation 2

Where:

- **Human factors** = \(\frac{\sum_i \text{Window Area}}{\sum_j \text{Wall Area}}\)

- **Technical factors\textsubscript{1}** = \(\frac{\text{Energy}}{\text{vol}}\)

- **Technical factors\textsubscript{2}** = \(\frac{\# \text{ of unsatisfied constraints}}{\# \text{ of constraints}}\)

- **Economic factors** = \(\frac{\text{Construction Cost}}{\text{Vol}}\)

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 unique situations. Two technical dimension measurements have been accounted for in Equation 2, Energy per volume and the degree to which constraints were met. These two
dimensions comprise the technical dimensions component while economic and human dimensions are represented through one numeric measurement. Despite the fact the calculation accounts for two measurements of technical measurement of the design, these sub calculations represent two unique performance aspects of the design artifact, energy consumption and attention to design criteria. Student CLMS_A069 designed a home with the following dimensions:

- Human dimension: \( \Sigma \text{Window area} = 42.71 \text{m}^2, \Sigma \text{Wall area} = 143.33 \text{m}^2 \)
  \[ \frac{42.71}{143.33} \approx 0.308 \]  percentile (top performance in sample)

- Technical\(_1\) dimension: Energy consumption = -3,621 kWh, Volume of home = 1,474.8 m\(^3\)
  \[ \frac{-3621}{1474.8} \approx -2.46 \]  percentile

- Technical\(_2\) dimension: All constraints met
  \[ \text{61st percentile (reflecting the majority of students meeting constraints)} \]

- Economic dimension: Construction cost = $214,573, Volume of home = 1,474.8 m\(^3\)
  \[ \frac{214573}{143.33} \approx 1454.48 \]  percentile

\( CLMS\_A069 \) Trade-off Value
\[ + 58 + 61 + 2 = 111 \]  (top overall Trade-off Value in sample)

**Results & Discussion**

The purpose of this study was to develop a method to calculated 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, I demonstrate how the Trade-off Value method addresses these three requirements. I 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. Figure 18 is a box plot that shows the distribution of Trade-off Values for the samples including quartiles, median, minimum, and maximum scores. This figure will be referenced in the describing the detailed results and discussion in the following subsections. The results and discussion will begin by showing how the Trade-off Value protocol encompasses multiple complementary and competing dimensions. Next, through presenting student design artifact examples, this section will suggest that the Trade-off value protocol provides a lens for noticing patterns in student design priorities. These student examples will
illustrate how the protocol can be applied consistently and systematically. Finally, this section will discuss how the student patterns revealed through the Trade-off Value protocol are indicative of design competency.

Figure 18. Trade-off Value sample distribution box plot

**Trade-off Value: Multiple complementary and competing dimension**

Figure 18 shows the range of student Trade-off Values, that will be further discussed through student examples in the following subsections. This section presents patterns of variation that we see from a close examination of the Trade-off Value. After calculating a Trade-off Value for each student design artifact, I took an etic approach to thematically analyze the collective group of student design artifacts to discover patterns. This analysis involved looked at each design artifact and Trade-off Value to uncover scenarios of focus on a single dimension (i.e., energy, cost, aesthetics) and scenarios in which a design artifact has balanced dimensions. In doing so, I identified five distinct patterns of variation in artifact quality which suggests patterns in ways students address multiple complementary and conflicting design dimensions. The Trade-off Value makes visible patterns of multiple dimensions (i.e. technical, human, or economic) collectively balanced versus a focus on a single dimension. The following section describes five patterns of variation that emerged from examining the results of the Trade-off Value analysis: (1) optimizing (minimizing) energy consumption, (2) minimizing costs, (3) maximizing aesthetics through large
windows, (4) disregard for livability, and (5) balanced trade-offs. My goal in looking into these patterns of variation are to understand if the Trade-off Value does indeed depict design artifact quality that encompasses multiple complementary and competing dimensions. Within each Trade-off Value pattern group, I include descriptions of representative students whose designs embody that pattern. In this description, I include figures of the final design artifacts as well as graphs that represent student Trade-off Value performance (both total sum and individual components of Trade-off Value) for that representative student.

**Pattern of negative energy consumption goal**

The design prompt explicitly directed students to minimize the energy needed for their designed home. Aligned with this goal, analysis of the generated Trade-off Value suggests that some students focused mostly on the technical aspect of their design, minimizing the annual energy consumption. Figure 19 and Figure 20 show representative designs of two students who employed this strategy. As shown here, both created a relatively simple form with few windows and a high number of solar panels, and both had a quality score in the top quartile of the Trade-Off Value for their school. Figure 21 and Figure 22 depict each of the students’ Trade-off Value in relation to the distribution of overall Trade-off Values at their respective schools. The left-hand side of the graph is box plot that shows the distribution of Trade-off Values for the sample including quartiles, median, minimum, and maximum scores with the specific artifact Trade-off Value note with an (*). Figure 21 and Figure 22 also include each of the four contributions to the overall Trade-off Value for each student: their percentile performance with respect to technical dimensions (constraints and energy consumption), human dimension (window-to-wall ratio), and economic dimension (construction costs). The student’s performance is denoted by a star (*) in those figures.
Figure 19. Student EMS_C018 design artifact

Figure 20. Student EMS_C006 design artifact
Figure 21. Student EMS\textsubscript{C018} artifact performance relative to sample

Figure 22. Student EMS\textsubscript{C006} artifact performance relative to sample
As shown in these figures, the technical dimensions, particularly energy consumption, appear to be the main focus although their overall Trade-off Value is also in the top quartile for both students (top 100 of approximately 400 total students). Students achieved a low energy consumption, yet their design quality suffered in areas such as overall aesthetics and livability demonstrated through the wall-to-window ratio. The two cases presented for this group show that even when employing a design strategy of minimizing energy consumed, the overall performance of the home varied depending on the extent to which the student focused on the other dimensions of technical constraints, cost, and aesthetics. For example, the poor performance of Student EMS_C018 in the human component of the design (Figure 21) placed this student only in the top half of the class despite good energy, moderate costs and meeting constraints. On the other hand, Student EMS_C006 also produced a design artifact with low energy consumption. However, the additional performance with respect to cost and windows led to this design performing overall within the top quarter of the class as shown in Figure 22. This group of students produced a design artifact that emphasized the technical dimension primarily, at the expense of human and economic dimensions. In focusing their attention on one aspect of their design, these students are behaving as beginning designers.

**Pattern of minimizing construction costs**

The design prompt explicitly directed students to minimize construction cost of their home, with a limit of $250,000 (see Table 13). Some students appeared to use this guidance as a goal to design as cost effective of a home as possible. Representative designs of two students who employed this strategy, one from each of the two schools are shown in Figure 23 and Figure 24. Figure 25 and Figure 26 depict each of the students’ performance relative to their school. Despite a minimal overall construction cost the area of the home was quite small, so the cost per area was not as effective in producing a livable space. As a result, Student EMS_B025’s 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 low cost at the expense of not reducing energy consumption. Notably, the artifact did not meet all of the technical criteria 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. Student CLMS_313’s design artifact of optimizing the cost at the expense of other
dimensions showed a similar pattern. Sacrificing size of the home for cost, in addition to not including a window on each side of the house, as specified in the design criteria, resulted in a Trade-off Value in the bottom portion of the class.

Figure 23. Student EMS_B025 design artifact

Figure 24. Student CLMS_C313 design artifact
Figure 25. Student EMS_B025 artifact performance relative to sample

Figure 26. Student CLMS_C313 artifact performance relative to sample
The two examples within this group show two examples indicative of students who employ a design strategy of minimizing construction costs. Even though these examples differ slightly on the other dimensions, they are characterized by the emphasis on optimizing costs. This 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 (such as student CLMS 313). These homes were also smaller than the others within their classes. Therefore, on a cost-per-square-foot basis these homes were not as effective. This group of students produced a design artifact that emphasized the cost dimension primarily, at the expense of human and technical dimensions. In focusing their attention on one aspect of their design, these students are behaving as beginning designers.

*Pattern of maximizing aesthetics through large windows*

A third pattern illustrated by the Trade-off Value protocol is maximizing aesthetics through large windows. Figure 31 and Figure 32 show representative designs of two students who employed this strategy. Figure 29 and Figure 30 depict each of the students’ performance relative to their school. From analyzing the two students’ designs (EMS_B014 and CLMS_A132) who are indicative of this pattern seems to suggest that optimizing a particular feature (window-to-wall ratio) while still working within the design criteria and constraints allows a moderate level of performance. Student EMS_B014 designed a home that included large windows on each wall, and performs at the top of the class 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 class (low percentile rank of 5.8). In addition, the construction cost of the house was high in relation to the rest of the class due to the large windows (low percentile rank of 16.67). The design also met all required design criteria and constraints and due to the large number of students who also met the constraints scored in the top 75th percentile. The artifact produced by student CLMS_A132 exhibited a similar pattern of very large windows, moderate energy consumption, and high cost while meeting design criteria and constraints. In both cases, the design artifact performed near the median for the class.
Figure 27. Student EMS_B014 design artifact

Figure 28. Student CLMS_A132 design artifact
Figure 29. Student EMS_B014 artifact performance relative to sample

Figure 30. Student CLMS_A132 artifact performance relative to sample
The examples 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 score. This group of students produced a design artifact that emphasized the human dimension primarily, at the expense of technical and economic dimensions. In focusing their attention on one aspect of their design, these students are behaving as beginning designers.

**Pattern of disregard for livability**

A fourth pattern among Trade-off Values appeared to have an opposite focus from the last pattern in attending to the human dimension of design. Figure 31 and Figure 32 represent designs of two students who seemed to neglect the livability, or human dimension, of the design. Figure 33 and Figure 34 depict each of the students’ performance relative to their school. Neither of the students’ designs feature windows, resulting in not only a jarring appearance but also not meeting the criteria for a window on each wall. The two homes had the same energy score (energy consumption percentile rank of 87.25) and both performed in the lowest quartile of the class overall (See Figure 34). The main distinction between these two homes was the degree to which design criteria were met. EMS_A015 failed to meet the window requirement and the size requirement whereas CLMS_A444 only failed to meet the window requirement. Their overall Trade-off Values reflect the lack of focus on design criteria.

Figure 31. Student EMS_A015 design artifact
Figure 32. Student CLMS_A444 design artifact

Figure 33. Student EMS_A015 artifact performance relative to sample
The pattern of neglecting particular features of the house (i.e. NO windows) combined with not meeting all design criteria and consults results in poor performance relative to the whole class. This group of students produced a design artifact that seemed to ignore livability (human dimension) and the economic dimension. The artifacts’ 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, these students are behaving as beginning designers.

**Pattern of balanced trade-offs**

Overall, the higher Trade-off values appears to indicate at least a moderate level of performance for each of the design dimensions of economic, human, and technical while meeting all design criteria. For example, 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.
Figure 35 and Figure 36 show representative designs of two students who employed this strategy of considering the dimensions of economic, human, and technical. Figure 37 and Figure 38 depict each of the students’ performance relative to their school. Student EMS_C019 designed a very effective cost house (85th percentile). The energy consumption is in the top 30% performance of the class, and window-to-wall ratio is in the top half. Overall, this is a basic but mostly attractive design (See Figure 35). No one area was optimized but the result is a livable house that performs well against cost constraints and energy goals. The artifact produced by Student CLMS_A069 is attractive design, with a large proportion of windows resulting in high performance in the human dimension. In addition, this artifact performed well in the cost dimension, while performing just above the median of the class for the energy dimension. This artifact seems to reflect no one area of optimization as energy consumption is effective but moderate, while cost and human dimensions appear to have been slightly more of a focus.

Figure 35. Student EMS_C019 design artifact
Figure 36. Student CLMS_A069 design artifact

*TOV = 288.72

Figure 37. Student EMS_C019 artifact performance relative to sample
This final pattern of student artifacts reflects at least moderate performance among all three dimensions (human, technical, and economic), with a slight push towards optimal performance with one dimension. This is a different pattern from the previous 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 their attention making balanced trade-offs within their design artifact, these students are progressing towards behaving as informed designers.

**Trade-off Value: Can be applied consistently and systematically**

The Trade-off Value protocol can be applied consistently in many scenarios because it a function of setting quantitative parameters (i.e. across technical, and economic dimensions). The Trade-off Value is quantified as performance outcome and is thus measurable. The overall score and each dimension sub score are not subject to interpretation in rating or judging. However, how each dimension is included as a metric may be subjective (but then applied consistently and systematically). For example, the Trade-off Value can be applied to a subjective idea such as livability but allows a clear and consistent measurement protocol for this subjective idea.
The Trade-off Value protocol is also easy to use. As a first step, the user needs to set parameters to measure within human, technical, and economic dimensions. Then, the user 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). Finally, the user will compute the percentile ranks of each dimension, summing the individual dimension ranks for the total Trade-off Value.

**Trade-off Value: Is indicative of design competency**

Four of the five patterns of design artifacts discussed in this chapter bear resemblance to what we would expect to see in beginning designers with respect to making trade-offs. While informed designers are skilled at weighing 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, pro or con, of a design (Crismond & Adams, 2012). In this study, the tendency to focus only on one aspect of a design is evidenced by a high score on one dimension, but a lower and problematic score on another dimension resulting in an overall Trade-off Value in the lowest quartile for the class. The patterns of optimizing energy consumption, minimizing costs, and maximizing aesthetics through large windows in particular speak to a beginning designers’ level of only focusing on 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). Therefore, the pattern of disregard for livability reflects this tendency of beginning designers as this group of students did not attend to the human dimension of a design artifact through livability. The final pattern of balanced trade-offs reflects those students who appear to be moving towards informed design practices by taking a more comprehensive approach to weighing the complex dimensions in a design artifact, evidenced by their overall performance within each of the four dimensions and holistically through their overall Trade-off Value. The composite Trade-off Value for this set of design artifacts is high. 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 us to understand how students address trade-off dimensions in producing design artifacts. The overall score allows a glimpse into the degree that 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 consider multiple dimensions with a predominant focus on technical, human, or economic dimensions. A smaller proportion of these students consider competing dimensions through either a balanced approach to making trade-offs or through an approach that follows a main focus while not neglecting other dimensions. For example, the pattern of maximizing aesthetics through large windows appears to have a focus in making the home livable also fulfills design constraints of at least one window per wall, but carries noticeable cost for the windows, and might positively or negatively affect energy. In brief, this study features designers with limited experience exhibiting patterns of narrow focus and balanced 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. A sub-score of, say, high performance for energy with low performance in human and cost dimensions would suggest that this student is making trade-offs in design like a beginning designer. Conversely, a high composite Trade-off Value and a lack of neglecting Trade-off Factor sub-scales might indicate a developing competency in design, particularly with respect to design decisions.

Conclusions & Implications

In measuring design products, there is a need for research models that “strive to more clearly identify the sets used, the discriminating objectives considered and the measurement systems” in order to facilitate “better communication, understanding, and results.” (Otto, 1995, p. 100). The Trade-off Value is a useful method to communicate the overall effectiveness and 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 while being systematic is also 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 could be a useful tool for students, educators, and researchers. As noted in a review of existing designer and researcher tools used to assess quality, the Trade-off Value protocol can be used in assessment of the ideation phase or of a final prototype, especially in situations where performance data is easily accessible such as Energy3D. Therefore, this the
Trade-off Value has potential utility as a formative or summative assessment tool in these kinds of situations. For students and educators, this would facilitate feedback for improvement in subsequent designs and would help create an understanding of the comprehensiveness to which a student addresses design dimensions. The overall Trade-off Value and the sub-scales could help students see shortcoming in their designs by making visible the attributes they were ignoring at the expense of optimizing something else. The Trade-off Value protocol could be useful in preparing and familiarizing pre-engineering students with an awareness of the inherent trade-offs involved in engineering design. For example, pairing the Trade-off Value with a discussion of design artifact performance on the whole as well as along each dimension as well as a reflection of the pros and cons of their design artifact might help students understand the strengths and weaknesses of their artifact and could lead to an informed process of iteration and improvement.

Researchers would welcome this method of design artifact assessment because it is grounded in the definition of design trade-offs, is systematic, and is easy to use especially when performance dimensions are measurable. Design quality measures can reduce quality to a single or small set of dimensions that are not fully representative of performance, and the Trade-off Value method avoids the limitations of such approaches. The Trade-off Value protocol produces a total score while also producing scores along each dimension which allows insight into not only overall design artifact performance but also performance within competing and complementary dimensions. This insight could be used to improve overall design artifact performance through attention to the relationship between design dimensions. As such the Trade-off Value protocol could have value in research investigating relationship between design quality and design behaviors as this protocol would allow for systematic calculation and would also more fully represent performance of a design artifact through a high-level score and intermediate dimension scores.

In future research, I 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 test with design challenges outside of the Energy3D platform in order to more fully comprehend 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.
Validity and reliability

Walter, Sochacka, and Kellam (2013) have provided an integrated framework for quality in interpretive engineering education research. Their Q³ Framework (Qualifying qualitative research quality) (Walther, Sochacka, & Kellam, 2013) presents six different quality considerations in interpretive research: theoretical, procedural, communicative, and pragmatic validation, ethical validation, and process reliability in research design and data interpretation. In designing this study, I addressed theoretical validation by collecting data in the students’ natural school setting in an authentic task that allows me to understand their design trade-off decisions. In order to address procedural validation, Walter et al. (2013) remark that eliciting students’ theories in action are more representative of their behavior than self-assessments of their learning. In that light, I collected student design artifacts as evidence of the enactment of their trade-offs. All students designed in Enery3D and were given the same design challenge. In handling the data, I systematically documented the many iterations of the Trade-off Protocol and tested the protocol through multiple sample sets (see Goldstein et al., 2016). Communicative validity attempts to establish shared interpretation with both internal and external “customers” of the research (Walther et al., 2013). I presented the trade-off value as a measurement of quality at the 2016 IEEE Frontiers in Education and received comments that others find this framework meaningful and adaptive, and further tested the protocol to understand meaningful variations in student trade-off profiles. Pragmatic validation concerns “data gathering in different cultural settings and with a diverse group of students” (Walther et al., 2013, p. 647). I incorporated the two schools in this study that are quite different from each other in terms of resources and diversity (See Chapter 1), in order to address a more diverse group of students. The investigation suggests that there are patterns in how beginning designers make trade-off decisions. This finding corresponds with others’ view of beginning designers (Crismond & Adams, 2012) but gives great detail outside of a dichotomous behavior. Ethical validation concerns aspects of integrity and responsibility through the research process. This study followed Purdue Internal Review Board (IRB) protocol, as discussed in Chapter 1. Finally, process reliability concerns the mitigation of random influences on the research process. All students were introduced to the software, Energy3D through a similar tutorial, either recorded or from a Purdue researcher. Then students were allowed a day to explore the software before attempting to address the design challenge so that we were more able to study students’ design artifact strategies rather than their explorations of a CAD software. In addition, the
systematic nature of the Trade-off Value protocol and consistent performance measurement within Energy3D allows a reliable calculation for interpretation.

**Limitations**

While the Trade-off Value protocol of assessing design artifact quality offers affordances of current methodological approaches and tools, there are some limitations. The Trade-off Value in its current form assigns equal weighting of importance among all design dimension. However, the equation could be modified to account for assigning a weight 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 ranks which makes the evaluation group dependent. For instance, a particular student’s tradeoff 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 classes for a design quality score for research purposes. Relatedly, this calculation method requires the same design task or a design project with easily comparable performance criteria because percentile-based performance requires a similar scale for comparisons across designs.

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 but also creates a need for consideration of the goal and how the individual criteria fit in this goal. However, once that judgement of criteria is made, the protocol can be applied consistently. For example, adding an extra design criteria 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 tested the Trade-off Value protocol in the context of a design task in Energy3D. A feature of Energy3D allows clear quantification of performance in areas such as cost and energy consumption. The Trade-off Value is certainly not limited to use in this context, but will require consideration into ways that competing dimensions can be quantified.
Acknowledgments

My extreme gratitude to my co-authors, Dr. Robin Adams and Dr. Senay Purzer. I appreciate the data organization and analysis support from undergraduate research assistant, Sharifah Omar, as well as the collaboration from our colleagues, Charles Xie and Jie Chao, at the Concord Consortium. I am grateful for the students who participated in this study and for their teachers who supported data collection efforts. This work presented in this manuscript 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 chapter are my own and do not necessarily reflect the views of the funding bodies.
CHAPTER 4. AN INVESTIGATION OF THE RELATIONSHIP BETWEEN STUDENT DESIGN RATIONALE AND QUALITY OF DESIGN SOLUTION

Abstract

Experienced designers hold a deep understanding of design trade-offs, which inherently influence their design decisions and ultimately their designed products. Similarly, the quality of student design products can be influenced by their understanding of trade-offs required in designing quality solutions. This research seeks to provide an interpretation of student designers’ trade-offs through the analysis of their design artifacts and design rationale. Through the context of an in-class individual design challenge, we collected data from over three hundred middle school students including (1) the final design products, and (2) a post-challenge design reasoning elicitation problem. We characterized patterns of student trade-offs through the Dual-Process Framework for Evaluating Student Design Trade-offs. The analysis started with the calculation of artifact quality score (called Trade-off Value) for each student and the scoring of the design reasoning problem through a content analysis of student responses. We used a cluster analysis to identify groups exhibiting distinct patterns of trade-offs as evidenced from these two scores. Results suggest that students were able to understand trade-off decisions consistent with beginning designers, and that students fit into four main patterns of their approaches in experiencing and analyzing trade-off decisions. These findings suggest a more comprehensive look at students’ abilities to make trade-offs would allow teachers to understand both where learning failures are taking place and where trade-off connections are happening.

Keywords: engineering design education, decision-making, trade-offs, design judgement, design rationale, pre-college engineering

Introduction & Motivation

People make decisions every day from the most mundane to the most critical decisions wrought with risk and uncertainty. The direction or quality of decisions can be impeded through a number of ways such as improper information gathering, misidentification of alternatives, or
improperly prioritizing criteria (National Research Council, 2001), but most importantly by a limited understanding of the need for balancing benefits and trade-offs (George, 2014). Trade-off decisions require a nuanced evaluative judgement in the decision-maker. In design, practicing engineers are reflective about the trade-offs involved in their design decisions and explicit in the design strategies on which they rely to arrive at a design solution (Atman et al., 2007; Crismond & Adams, 2012).

Recent calls to include engineering design as part of a K-12 curriculum (National Research Council, 2012a, 2013) present opportunities for meaningful learning of 21st Century Skills (National Research Council, 2012b) that are also central to design learning, such critical thinking and decision-making (McCormick & Hammer, 2016). Despite the availability of guidelines for elements of an appropriate precollege engineering education (Moore et al., 2014) there is a dearth of research characterizing K-12 students’ abilities to make trade-off decisions in engineering design with most research focusing on collaborative decision-making (Bethke Wendell & Rogers, 2013). Moreover, understanding the connection between student decisions and the quality of their work is under-researched (Tai, Ajjawi, Boud, Dawson, & Panadero, 2017).

This study seeks to characterize student trade-off decision profiles through understanding: (1) students’ ability to provide design rationale, and (2) how this ability relates to quality of their own engineering design work. This work asks the following research question:

1. To what extent do pre-engineering students understand trade-off decisions as evidenced by their ability to evaluate alternative solutions with multiple trade-off factors?
2. What are the patterns of design trade-off decisions in pre-engineering students?

This investigation is important from two perspectives. First, one of our important goals as educators is to develop students with abilities to solve problems. Problem solving judgment or evaluative judgement is one of most important goals of education (Jonassen, 2000; Tai et al., 2017). Second, we want to develop students with a deep understanding of trade-offs, criteria, and constraints that govern design decisions. An understanding trade-offs is necessary as a form of design competency and key feature of design performance (Goldstein, Purzer, & Adams, 2016).
Background and Theory

Making decisions is an important part of much engineering work. Practicing engineering designers often make decisions while working with competing design criteria (e.g., Abbas & Howard, 2005; Behdad, Kwak, Kim, & Thurston, 2010; See & Lewis, 2006). These decisions are also made under uncertain conditions (e.g., Carnahan & Thurston, 1998; Katsikopoulos, 2012; Sha & Panchal, 2014; Thompson & Paredis, 2010; Thurston, Lloyd, & Wallace, 1994). Engineering design decision-making as a research field has become a distinct area within the engineering design community over the last 30 years, as “members of the design research community articulated a growing recognition that decisions are a fundamental construct in engineering design” (Chen, Lewis, & Schmidt, 2006, p. 5), with a need for research substantiated by support and funding through the National Science Foundation. Because practicing engineering designers are required to make decisions in their work setting, the National Academy of Engineering report, *Theoretical Foundations for Decision Making in Engineering Design* (2001), recommends decision-making be included in undergraduate engineering design courses and recommends that further research is needed to understand how to best integrate decision theory and tools into an undergraduate education. Similarly, The National Academies report, *A Framework for K-12 Science Education*, (National Research Council, 2012) states the need for integrated science and engineering learning in precollege and highlights the importance of decisions: “Engineers, too, make decisions based on evidence that a given design solution will work; they rarely rely on trial and error” (National Research Council, 2012, p. 62). These two National Academy of Engineering reports stress that decision-making is a large part of the work of engineers, and should therefore be taught at both the undergraduate level and the precollege level.

Despite the calls for trade-off thinking to be incorporated in design teaching and learning, much research in K-12 trade-offs has been limited to a socio-scientific context (Albe, 2008; Brotman et al., 2010; Lee & Grace, 2012; Papadouris, 2012a; Papadouris & Constantinou, 2010; Ratcliffe, 1997; Schkade & Payne, 1994; Seethaler & Linn, 2004; Siegel, 2006), without a focus on student designers. Socio-scientific issues are often used in the pre-college classroom as a way to deeply discuss scientific topics through dialogue, discussion, and debate (Zeidler & Nichols, 2009). These issues are often controversial and require students to make decisions after moral debate on the subjects (Zeidler & Nichols, 2009). Through this moral reasoning, students are expected to address “scientific misconceptions, lack of personal experiences, lack of content
knowledge, underutilized scientific reasoning skills, and emotional maturity” (Zeidler & Nichols, 2009, p. 52). While two relevant studies (Doppelt, Mehalik, Schunn, Silk, & Krysinski, 2008; Mehalik, 2008) compared middle school student science performance in a design curriculum versus a traditional curriculum, the extent to which students made trade-offs was not a focus outside of a scaffolded decision matrix. However, past related research has hinted at variations in student trade-offs while investigating design behavior patterns. For example, two studies with high school students (Goldstein, Purzer, Zielinski, & Adams, 2015; Purzer et al., 2015) showed that there are variations in how students demonstrate balancing benefits and tradeoffs in making design decisions. Results from Goldstein and colleagues (2015) showed that students became increasingly reflective with each subsequent design iteration and that their reflections referred to a particular aspect of their design rather than to analysis of trade-offs or scientific concepts. Purzer, et al. (2015) showed meaningful science learning through engineering design occurred when students attempted to balance benefits and trade-offs, as evidenced through their reflections and design actions. A third related study investigated the connection between student reflection and informed design strategies through quantitative analysis (Goldstein, Purzer, Adams, & Xie, 2015) laying the groundwork for understanding student design decision-making rationale through reflections.

This literature review begins by situating design at the center of engineering and engineering education before defining design decision-making and design trade-offs. Then, the chapter presents a synthesis of studies on students’ abilities to make trade-offs and a synthesis of literature in teaching trade-off decision making and evaluative judgement. This literature leads to the development of a conceptual framework, the Dual-Process Framework for Evaluating Student Design Trade-offs based on Paparouris’s (2012) depiction of dual-process decision-making and Asimow’s (1962) definition of design as a system of tradeoffs. Finally, I use the Dual-Process Framework for Evaluating Student Design Trade-offs to understand pre-engineering designers’ trade-off decisions in the present study.

**Design is central to engineering and engineering education**

Design is the distinguishing activity of engineering (Dym, 1994; Dym et al., 2005). Dym, et al. (2005) 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” (p. 104). Bucciarelli (2003) explains that engineering design is a “social process of negotiation, or iteration, of rectifying missteps, even misconceptions – a process rich with ambiguity and uncertainty” (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).

Because design is so critical to the engineering profession, it is a core focus in engineering education at the college level (Atman, Eris, McDonnell, Cardella, & Borgford-Parnell, 2014). Design is also critical for businesses and for innovation (George, 2014; Kelley, 2001). Additionally, engineering education at the K-12 level also emphasizes design as a key practice and a disciplinary core idea in engineering in the Next Generation Science Standards (NGSS) (Achieve, 2013). Hence, design has become an educational focus for all regardless of whether they pursue engineering or not.

**Engineering design involves decision-making and trade-offs**

Making decisions is an important part of much engineering work. In fact, some describe design as a series of decisions (Ullman, 2001) noting that design problems require a designer to make many decisions throughout the entire design process (Akin & Lin, 1996). In a meta-synthesis of literature highlighting the differences in behaviors of beginning versus informed (or “engaged and knowledgeable”) designers, Crismond & Adams (2012) discuss “weigh options and make decisions” as one of the nine critical design practices. In particular the behavior of “weigh options and make decisions” is a distinguishing area for informed designers in terms of decision-making skill. Practicing designers work through complex and ill-structured problems that require both weighing options and forecasting the impact of these decisions (Strobel & Pan, 2010). Informed designers are skilled at “weighing and articulating” (Crismond & Adams, 2012, p. 761) both the pros and cons of a particular design solution, and can look for trade-offs in even the best ideas.

Trade-offs are a complex element of a decision, as the decision-making weighs possible outcomes against their respective costs (Otto & Antonsson, 1991). Although trade-offs in design
are inevitable (Wong et al., 2009), a design process where designers can examine trade-offs and develop alternatives is likely to lead to a higher quality design solution. The National Research Council (2001) 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 tradeoffs. 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” (NRC, 2001, p. 10).

Studying engineers in the workplace has suggested the importance of making trade-offs as a professional skill. In one such study (Jonassen, Strobel, & Lee, 2006) highlighted the importance of balancing competing needs and criteria as one of the attributes that differentiate workplace problems from school problems. In another investigation, Strobel and Pan (2010) examined engineering workplace problems through a multi-case comparison of 90 engineers and found engineers weigh options and estimate 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. Furthermore, design professionals not only make trade-off decisions, they also communicate their “optimization approach” in addressing aesthetics, functionality, buildability, and economics to clients (Wong et al., 2009), including internal team members and external stakeholders.

**Importance of students’ abilities to make design trade-off decisions**

Decisions are an integral part of engineering education at the undergraduate level. In fact, the Accreditation Board for Engineering and Technology (ABET) in specifying curriculum requirements (Criterion 5) define engineering design as:

“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” (emphasis added)

ABET also specifies that a crucial student outcome (Criterion 3) of an undergraduate engineering education includes:

“an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability”

Working within the constraints of economic, environmental, social, and more requires trade-off decisions. Therefore, ABET is requiring the students make effective design trade-off decisions upon completion of their engineering degree because it is an essential engineering practice.

Studies conducted in a college setting highlight large differences between the design processes of expert designers and the habits of undergraduate students. People in general, not only students, struggle with evaluating trade-offs between two attributes of very unequal importance where the option should be “obvious” (Scholten & Sherman, 2006), demonstrating that decision-making is not necessarily a naturally easy process. Prior studies with engineering college students identify weaknesses, especially in making trade-off decisions. For example, Younker and McKenna (2009) found that only 31% of first year engineering design teams supported their decisions with evidence, relying more extensively on self-generated assumptions rather than performance data. Girod and colleagues (2003) showed that design teams spent little time discussing the relative importance of design criteria. Implications from both studies indicate that students do not fully characterize their design options and do not reliably understand how to manage conflicting criteria.

Because engineering students experience challenges in making trade-off decisions, it is likely that pre-engineering students also face similar challenges. Despite the perceived difficulty, the development of decision-making skills and trade-off aptitude is broadly recognized as a significant learning objective at the K-12 level. The International Technology and Engineering Educators Association (ITEEA, 2007) describes what students should know and be able to do in order to be technologically literate in Grades K-12, with optimization and trade-offs noted as “core
concept of technology” for students because of society’s growing interdependency with technology. ITEEA (2007) contends that students need repeated exposure in determining trade-offs due to the importance of this skill and prevalence that trade-offs will be encountered. Similarly, the importance of trade-off skills in linking science knowledge with design knowledge is outlined in the Next Generation Science Standards (NGSS) (Achieve, 2013) Disciplinary Core Ideas (emphasis added):

ETS1.C: Optimizing the Design Solution

- Although one design may not perform the best across all tests, identifying the characteristics of the design that performed the best in each test can provide useful information for the redesign process—that is, some of those characteristics may be incorporated into the new design. (MS-ETS1-3)
- The iterative process of testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution. (MS-ETS1-4)
- Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed. (HS-ETS1-2)

At both the middle school and high school levels, this disciplinary core idea involves using judgement to compare and improve on proposed design solutions. By the end of middle school, students should be able to evaluate solutions with respect to how well they meet criteria and constraints to systematically understand why features in a particular design solution might perform “best.”

Teaching trade-off decision-making and evaluative judgement

Given the importance of trade-offs in design necessary for all students to develop, teachers need to understand how to best integrate effective decision-making for their students. In a more general educational context, the importance of evaluative judgement has been noted by several authors (Ajjawi & Higgs, 2008; Boud, 2000; Cowan, 2010; Sadler, 1989, 2010; Tai et al., 2017). Design rationale fits under the umbrella of evaluative judgment as evaluative judgement is “the capability to make decisions about the quality of work on self and others” (Tai et al., 2017, p. 5). These higher order evaluative skills can be developed through techniques of self-assessment, peer assessment, and the use of exemplars (Cowan, 2010; Tai et al., 2017). While this professional
judgement is a goal of many educational settings (i.e. “clinical reasoning” in medicine education and nursing education, “legal reasoning” in law) younger students can (and should!) begin making these evaluations in order to develop a foundation for sound decision-making.

**Conceptual Framework: Understanding student trade-off decisions**

The framing of engineering design in a seminal textbook, *Introduction to Design*, as 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) provides background for my definition of design trade-offs for this research as a means of accounting for multiple and competing technical, human, and economic dimensions in design decisions. Understanding student trade-off ability is complex. One way to approach how well students’ address trade-offs is through analyzing the performance of a final design artifact for a particular situation. Another way to understand trade-offs is through analyzing a student’s rationale for choosing among different designs, as a more general reasoning approach.

Decision-making has been described as a dual-process of thinking: experiential and analytic (Papadouris, 2012a). Experiential thinking processes are “automatic, fact, and effortless” while analytic thinking processes are “conscious, slow and effortful” (Papadouris, 2012, p. 602). This model of decision-making shares the idea of two-part decision-making with Jonassen’s depiction of a quality decision consisting of (1) decision effectiveness and (2) student ability (via argumentation or reasoning) (Jonassen, 2012). Decision effectiveness can be evidenced through the experiential case and student ability can be evidenced through their analytic process.

Building on Papadouris’s work, I developed a framework, *Dual-Process Framework for Evaluating Student Design Trade-offs*, that provides a two-part composition of student designer trade-off profiles through their *experience* (in the particular) and *analysis* (in the general) of design trade-offs (See Figure 39). In defining ‘general’ and ‘particular’ I refer to Adams, Atman, & Turns' (2003) depiction of Scardamalia & Bereiter's (1981) theory of expertise development translated to the context of design expertise. General refers to general domain knowledge, while particular pertains to specific cases. In this framework, we measure experiential thinking by evaluating the quality of a student’s design artifact (the particular). Experiential design trade-offs are evidenced by the effectiveness of a student design artifact in addressing competing and complementary criteria in a “synthesis of technical, human, and economic factors” (Asimow, 1962, p. 2).
The second element in the *Dual-Process Framework for Evaluating Student Design Trade-off*, is analytic thinking (the general). Unlike a design artifact, analytic thinking is difficult to make visible. In this framework, analytic ability is based on the justification a student provides in evaluating alternative design solutions. Here, justification or “rationale” is measured using Asimow’s depiction of a multifaceted synthesis required in design. In other words, the more connections students make to technical, human, and economic dimensions, the more fully they have reasoned through a design trade-off decision.

![Diagram of Dual-Process Framework for Evaluating Student Design Trade-offs](image)

**Figure 39. Dual-Process framework for evaluating student design trade-offs**

This dual-process framework bears resemblance to research on the acquisition of literacy and writing expertise (Scardamalia & Bereiter, 1981) with domain knowledge consisting of two parts: (1) general domain knowledge, and (2) a particular case representation of a problem. As shown in Figure 40, these two elements interact through domain knowledge being used to interpret a particular case. Developing expertise involves repetitive movement between two elements: (1) the abstract (or the general) and (2) the concrete (or the particular) (Maton, 2013; Wolmarans, 2016). We want students to go back and forth between general and particular knowledge in an area because this movement between concrete and abstract understanding of a concept is important for cumulative or deep learning (Clarence, 2017; Maton, 2013) and requires an understanding of dual knowledge. Specifically, for trade-off decisions we want students to understand trade-offs as an abstract concept, unpack that concept, apply trade-offs in a design example, repack trade-offs to
build their own meaning as an abstract concept and cycle through these “waves” of developing particular and general knowledge.

![Diagram showing the process of acquiring deep and cumulative trade-off knowledge](image)

**Figure 40.** A depiction of the process of the acquisition of deep and cumulative trade-off knowledge (based on Scardamalia & Bereiter, 1981)

### Research Methods

**Students and Design Challenge**

This study was conducted with 318 7th grade students at a large, suburban middle school in the Midwest, United States in the Spring of 2017. Students participated in an in-class design project using Energy3D, (http://energy.concord.org/energy3d/), a CAD simulation environment that allows students to design, analyze, and construct green buildings (Xie et al., 2018). Researchers introduced Energy3D through a presentation that discussed engineering design in general and the challenge in specific. Students were then given time to learn the software through free-play or a small design challenges. When it came time to begin the design challenge, all students were given two-page design specifications sheet that summarized the details from the presentation. For the challenge students were asked to use Energy3D to create single-family homes that (1) minimized energy consumption, (2) minimized construction cost, while (3) designing a
house large enough for a family of four, and (4) maintaining an attractive appearance. At the conclusion of two weeks students produced two to three final designs in Energy3D saved as log files. In addition, they took a post-test assessment. (See also Chapter 1 for more details.)

**Data Sources**

Two main sources of data were collected and analyzed in this research: students’ design artifacts (i.e., Trade-off Value described in detail in Chapters 1 and 3) an opened-ended Design Rationale Elicitation Task.

**Design artifacts**

Students developed solutions, which I call design artifacts, within the Energy3D platform which were saved as electronic files. Each Energy3D design file includes key design performance information including total annual energy consumption and total construction costs. Design specifics such as area of home and number of solar panels are also saved in this final file. This information can be converted into a Trade-off Value through the use of the Trade-off Value protocol described in Chapter 3. Overall, Trade-off Value is calculated by summing the percentile ranks of student performance relative to a population sample in human, technical, and economic dimensions.

**Design Rationale Elicitation Task**

Students completed the *Engineering Science Test in Sustainable Design* through an electronic survey platform at the conclusion of their design project (Goldstein, Omar, Purzer, & Adams, 2018). This post-test included an open-ended design rationale question, the *Design Rationale Elicitation Task*, repeated here from Chapter 1, which asked students to explain their reasoning in selecting a design solution from three alternatives. As shown in Figure 41, students are told that an engineer needs to balance trade-offs between energy and cost while making sure enough light enters the building. The performance data provided for each of the three options were created such that there is no obvious choice or one correct answer. In addition, the variety of performance data provides opportunities for students to make connections between the benefits and the trade-offs among the three buildings and across multiple dimensions (energy consumption, cost, livability, etc.) (See Figure 41).
An engineer is asked to determine the best option among three buildings. She needs to balance trade-offs between energy and cost while making sure enough light enters the building through windows.

<table>
<thead>
<tr>
<th></th>
<th>Building 1</th>
<th>Building 2</th>
<th>Building 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Net Energy Consumption (kWh)</td>
<td>-1,000</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Total Material Cost ($)</td>
<td>59,626</td>
<td>55,000</td>
<td>49,000</td>
</tr>
<tr>
<td>Volume (m$^3$)</td>
<td>160</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Number of Trees</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Total Wall Surface (m$^2$)</td>
<td>185</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Total Window Surface (m$^2$)</td>
<td>16</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

Using the information provided above, which building would you suggest the engineer selects?

a) Building 1  
b) Building 2  
c) Building 3

Please explain your choice:

__________________________________________________________________________________________


Figure 41. The Design Rationale Elicitation Task

Data Analysis

Data analysis involved multiple steps in order to understand students’ dual-process trade-off profiles through their experience (in the particular) and analysis (in the general) of design trade-offs (See Figure 42). First, I determined an experiential score for each student via Trade-off Value score. Next, I calculated an analytical score for each student via coded rationale. Finally, I
conducted a cluster analysis with the experiential and analytical scores to understand student trade-off clusters through the Dual-process Trade-off framework.

![Figure 42. Visual diagram of study analysis](image)

**Experiential Trade-offs through Calculation of Trade-off Value Score**

In order to understand how well students could implement trade-off decisions in the particular case, as evidenced from their design artifacts (experiential trade-offs), I followed the Trade-off Value protocol and calculated a quantitative representation of the degree to which a design artifact addressed human, technical and economic requirements. The composite Trade-off Value (see Equation 2) is the sum of percentile ranks of student performance relative to the class, and is a score of 0-400.

\[
\text{Trade-off Value} = \sum_i \% \text{ilerank(Human factors)}_i + \sum_j \% \text{ilerank(Technical factors)}_j + \sum_k \% \text{ilerank(Economic factors)}_k
\]

Equation 3
Analytical Trade-offs through Analysis of the Design Rationale Elicitation Task

The analysis of student responses assessed the extent to which students considered multiple trade-off factors in the general sense when making a design decision in the Design Rationale Elicitation Task. (See Table 15).

Two researchers performed a content analysis (Creswell, Plano-Clark, Gutmann, & Hanson, 2003) of students’ answers to the Design Rationale Elicitation Task using predetermined categories and codes to systematically categorize students’ answers to the Design Rationale Elicitation Task asking them to explain their decision and reasoning for selecting a design solution among three alternatives. These a priori codes were based on the definition of engineering design as “a synthesis of technical, human and economic factors” (Asimow, 1962). Each of the two researchers read each student response and coded the response in referencing each of the non-exclusive categories of human, technical, and economic dimensions (See Table 16). We identified responses with tradeoff connections when students used contrasting conjunctions such as

Where:

- **Human factors** = \( \sum_{i} \frac{Window Area_i}{Wall Area} \)
- **Technical factors**\(_1\) = \( \frac{Energy}{vol} \)
- **Technical factors**\(_2\) = \( \frac{\# \text{ of unsatisfied constraints}}{\# \text{ of constraints}} \)
- **Economic factors** = \( \frac{Construction Cost}{Vol} \)
‘although’, 'but', and ‘whereas’ as these words reflect students’ attempts to connect the positive aspects to negative aspects of the design solution, which is consistent with skill theory (Fisher, 1980, 2006; Fischer & Bidell, 1998). Consequently, in our analysis the coding categories are not mutually exclusive, meaning students could make zero, one, two or three trade-off connections. We first implemented a binary coding system [1 0] in analyzing the responses, with 1 indicating that the particular trade-off dimension exists and was explicitly mentioned by the student. Then, we summed the total number of trade-off dimensions (0-3) in each student response. However, the fourth category ‘Vague Quality Reference’ is mutually exclusive from either of the first three categories. An additional code, ‘Vague Quality Reference,’ was created to categorize responses that simply listed the data presented in the question without a clear connection between these dimensions (e.g., “It consumes 0 energy and costs $55,00”).

Table 16. Design Rationale Elicitation Task trade-off coding scheme

<table>
<thead>
<tr>
<th>Code Category</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td>Student rationale explicitly references the energy efficiency or annual energy consumption of their choice. Students might reference the overall energy consumption</td>
</tr>
<tr>
<td>Human</td>
<td>Encompasses responses that reflect the livability &amp; aesthetics of the house including one or more of the following: ratio of window to wall, size of house, and number of the trees.</td>
</tr>
<tr>
<td>Economic</td>
<td>Student rationale explicitly mentions the construction costs of their selection. Does not include responses that discuss negative energy resulting in energy cost savings, as those responses are also coded as ‘technical’ and categories are not mutually exclusive.</td>
</tr>
<tr>
<td>Vague Quality Reference</td>
<td>This category encompasses student responses that simply list more than one trade-off dimension (technical, human &amp; economic) from the question prompt with no rationale. This category is mutually exclusive from the first three categories.</td>
</tr>
</tbody>
</table>

Two researchers independently analyzed and coded student responses according to the coding scheme. Cohen’s κ was calculated to determine the inter-rater reliability between the two
researchers. The resulting Cohen’s $\kappa$ value was .94 indicating substantial agreement (Landis and Koch, 1977) prior to resolving inconsistencies. Table 5 includes examples of students’ responses within the coding framework (See Table 17).

<table>
<thead>
<tr>
<th>#</th>
<th>Sample responses</th>
<th>Coding category</th>
<th>Number of trade-off connections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Technical</td>
<td>Human</td>
</tr>
<tr>
<td>1</td>
<td>“It is right in the middle.”</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>“it has the lowest energy consumption “</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>“It costs the less, and even though the net energy may be the highest, it still can be energy sufficient.”</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>“Although building one is slightly more costly, the difference of increase in cost is outweighed by how much more energy efficient it is compared to the other buildings. It also was the largest of them and has a decent amount of trees too.”</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 17 continued

<table>
<thead>
<tr>
<th></th>
<th>“uses less energy, gains money, and is bigger”</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Coding categories Technical through Economic are not mutually exclusive from each other, but are exclusive from Vague Quality.

**Pattern Identification: Cluster analysis**

My second research question focused on the identification of patterns of design trade-off decisions using the *Dual-Process Framework for Evaluating Student Design Trade-offs*. To identify groups of students who exhibited similar patterns across design artifact and design rationale task performance, I utilized cluster analyses. (See Appendix B for cluster analysis technical report). Clustering approaches can be described as hierarchical (agglomerative) or partitioning (divisive); hard (exclusive) or fuzzy or overlapping (non-exclusive); or deterministic or stochastic (Aldenderfer & Blashfield, 1984). I first performed agglomerative hierarchical cluster analysis using the Ward’s method for cluster distance in SPSS. This approach is “useful for exploratory work when researchers do not have a preconceived idea about the likely number of clusters in the dataset” (Antonenko, Toy, & Niederhauser, 2012, p. 385). I identified the number of clusters from visually inspecting the cluster dendrogram. After identifying four distinct clusters, I used a k-means cluster analysis to identify cluster membership for each student. A k-means cluster analysis in particular allows the researcher to select a number of clusters, making for meaningful groupings in a research context and is useful for large datasets (Aldenderfer & Blashfield, 1984). I selected four groups based on the results of the agglomerative hierarchical cluster analysis (see Appendix B) and used the k-means cluster analysis to find membership within those four groups. I then examined the differences across clusters with an analysis of variance (ANOVA) to confirm independent groupings. Using a threshold of $p<0.05$ ANOVA results indicated independence of means for both variables (Trade-off Value and Design Elicitation Rationale Task score) across the for clusters. This step is important in examining whether final clusters differentiate the data well and in examining whether the clusters are truly distinct.
Results

Descriptive analysis of design rationale and design quality

Descriptive statistics for artifact Trade-off Value and Design Rationale Elicitation Task scores are shown in Table 18 to give context regarding student performance within Experiential Trade-offs via Trade-off Value and Analytical Trade-offs via Design Rational Elicitation task score.

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>Tradeoff Value (n=318)</th>
<th>Design Rationale Task score (n=318)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>204.24</td>
<td>1.18</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>42.32</td>
<td>.84</td>
</tr>
<tr>
<td>Minimum</td>
<td>81.25</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>310.84</td>
<td>3</td>
</tr>
<tr>
<td>Range</td>
<td>229.59</td>
<td>3</td>
</tr>
<tr>
<td>Median</td>
<td>208.91</td>
<td>1</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>181.25</td>
<td>1</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>237.12</td>
<td>2</td>
</tr>
<tr>
<td>Skewness</td>
<td>-.48</td>
<td>.19</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>-.22</td>
<td>-.71</td>
</tr>
</tbody>
</table>

A breakdown of distribution of student responses is presented in Table 19. While nearly a quarter of the students cited no trade-offs in selecting a design alternative, over a quarter discussed two trade-offs in either pro/con pairs or pro/pro pairs. The majority of students (41%) cited only one dimension for design alternative selection. Only 5.6% of the students discussed all three dimensions of trade-offs in their responses. Table 20 presents the frequency of each particular trade-off considered in the Design Rationale Elicitation Task. The majority of students cited low energy consumption as a reason for selecting a particular alternative. Construction costs (economic) were the next prioritized criteria followed by human considerations of windows, trees, and size of home. In general, students who cited one trade-off dimension on which they based their design alternative selection were apt to discuss a “pro” of the chosen design alternative such as
low cost (economic) or low energy consumption (technical) (e.g. “It has the least net energy consumption.”). In discussing two trade-offs students would either cite two “pros” (e.g. “It is bigger and uses less energy”) or might cite a “pro/con” pair (e.g. “There is 0 energy consumption, but its not too expensive.”)

<table>
<thead>
<tr>
<th>Student Rationale Level</th>
<th>Percentage of students (n = 318)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>24.7%</td>
</tr>
<tr>
<td>1</td>
<td>41.0%</td>
</tr>
<tr>
<td>2</td>
<td>28.7%</td>
</tr>
<tr>
<td>3</td>
<td>5.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Student Rationale Level</th>
<th>Percentage of students (n = 318)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td>56.8%</td>
</tr>
<tr>
<td>Economic</td>
<td>24.4%</td>
</tr>
<tr>
<td>Human</td>
<td>14.9%</td>
</tr>
<tr>
<td>Vague</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

**Table 19. Design Rationale Elicitation Task score breakdown**

**Table 20. Trade-off cited in Design Rationale Elicitation Task**

**Relationship between design rationale and design solution quality**

My cluster analysis sought to identify emergent groupings of pre-engineering students based on their dual-process design trade-offs. I identified a four-cluster solution as best fitting the sample data using guidance from a dendrogram from the first-stage hierarchical clustering, and proceeded to run a four-cluster k-means analysis (See Appendix B for dendograms and cluster analysis technical report). I labeled these four clusters as: *High Dual-Process Trade-offs*, *Analytical Dominant Trade-offs*, *Experiential Dominant Trade-offs*, *Low Trade-off Demonstration*, discussed in greater detail in the following paragraphs. Results of this analysis are shown in Figure 43, and include blue dashed lines that represent the 25th percentiles of student performance for the sample. The *High Dual-Process Cluster* is composed of students who exhibited high performance in both experiential and analytical design trade-offs. Students in the
Low Dual-Process Cluster produced designs that performed low in Trade-off Value (experiential) and performed at the 25th percentile in the Design Rationale Elicitation Task (analytical). Of particular interest are the Analytical-Dominant and Experiential-Dominant Clusters because students in these groups attended to either the analytical or experiential component. Students in the Analytical-Dominant Trade-offs Cluster tended to perform well on the Design Rationale Elicitation Task but produced design artifacts that performed in the bottom quartile for Trade-off Value within the sample. On the opposite end of the spectrum, students in the Experiential-Dominant Cluster produced design artifacts that exhibited high Trade-off Values, yet did not demonstrate an understanding of trade-offs in the Design Rationale Elicitation Task. The smallest clusters were the dual-process trade-off groups with the high dual-process cluster n = 36 and the low dual-process cluster n=27. The clusters dominated by a singular trade-off process were larger, with the Experiential-dominant cluster n = 161 and the Analytical-dominant cluster n = 94.

Figure 43. Student Trade-off profiles based on cluster analysis across Trade-off Value and Design Rationale Elicitation score

These clusters of students are important in understanding the variation in how students dually analyze design trade-off decisions (in the general) and experience design trade-off decisions (in the particular). Because we want to see students understand trade-offs from both perspectives for deep learning (Maton, 2013; Scardamalia & Bereiter, 1981; Wolmarans, 2016) taking a close look at groups of students who do not exhibit this dual learning might provide insight regarding their learning failures. Adams, Turns, and Atman in extending Scardamalia and Bereiter’s (1981)
theory of expertise development to the field of design stress that in order to develop design expertise, students should engage in “repetitive cycles between the general and the particular” (Adams et al., 2003, p. 18). In these repetitive cycles, students will use their design domain knowledge to address a particular design challenge. In addressing the design challenge, students will then acquire new information that will update their design domain knowledge, and will lead to new ways to respond to the next design challenge, in a continuing cycle. However, failure modes in this cycle exist that could limit students’ abilities to develop deep knowledge and include: “(1) failures of general-to-particular process (not having adequate knowledge to apply to the case or not having knowledge structured in a functional way), (2) failures of a particular-to-general process (solving a problem yet failing to learn or integrating generalizable knowledge into their existing knowledge structures), and (3) failures at an execution level (lack of knowledge checking procedures to determine if a solution makes sense)” (Adams et al., 2003, p. 18).

The following sections further describe each of the four clusters through a high-level summary of the cluster and through student cases illustrating their design artifact performance and Design Rationale Elicitation Task score. The student cases with examples of their design rationales and their Trade-off Value scores are summarized in Table 21.

<table>
<thead>
<tr>
<th>Cluster name</th>
<th>Student pseudonym</th>
<th>Trade-off Value score (out of 400)</th>
<th>Design Rationale Task response</th>
<th>Design Rationale Task score (out of 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High dual-process</td>
<td>Abby</td>
<td>310.84 (Top 25%: 1 of 318)</td>
<td>“It had a pretty good energy number. The cost was not low like building 3 but was not high like building 4, so it was a good price. It was a decent sized house. Good amount of trees.”</td>
<td>3</td>
</tr>
<tr>
<td>Analytical-Dominant</td>
<td>Brad</td>
<td>186.31 (Middle 50%: 225 of 318)</td>
<td>“This building is completely energy efficient, has the most amount of windows, but the highest cost because of these things but the amount of energy helps to [offset] the balance.”</td>
<td>3</td>
</tr>
</tbody>
</table>
### Table 21 continued

<table>
<thead>
<tr>
<th>Experiential-Dominant</th>
<th>Carlos</th>
<th>250.38</th>
<th>“Building 2 because it has 0 kWh and it is in between building 1 and 3.”</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Top 25%: 39 of 318)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low dual-process</th>
<th>Diana</th>
<th>115.17</th>
<th>“Has low kWh”</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Lowest 25%: 307 of 318)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### High dual-process trade-offs student case

Students with both high Trade-off Values and high Design Rationale Elicitation scores demonstrated high dual-process trade-offs. These 36 students produced design artifacts that embodied design competency with respect to understanding how to balance competing and complementary design criteria with a range of Trade-off Values from 253.44 to 310.44 out of a possible 400 (which maps to the 89th to 99th percentile). At the same time, these students were apt to discuss multiple trade-off factors that they would consider in choosing a best design alternative. One student, with the pseudonym Abby, designed the home shown in Figure 44.
This home, with a Trade-off Value of 310.84, consumed -3,621 kWh of energy annually with a resulting construction cost of $214,573 (compared to the maximum level of $250,00 while meeting all specified design constraints (e.g., each side of house must have at least one window, no more than 40 solar panels, etc.). This home also performed at the 99th percentile for the human component of the house as measured by the window-to-wall ratio as an indicator of “livability”. Additionally, Abby provided the following answer in the Design Rationale Elicitation Task, and discussed energy, cost, and livability for a high overall score of 3:

“It had a pretty good energy number. The cost was not low like building 3 but was not high like building 4, so it was a good price. It was a decent sized house. Good amount of trees.”

(Score: 3)
Analytical-Dominant trade-offs student case

Students with low Trade-off Values but high Design Rationale Elicitation scores comprise the Analytical-Dominant trade-off cluster. These 94 students produced design artifacts that did not demonstrate design competency with respect to understanding how to balance competing and complementary design criteria. Their artifact Trade-off Values range from 136.74 to 194.77 (which maps to the 11th to 41st percentile). However, students in this cluster scored high on the Design Rationale Elicitation task because they were likely to discuss two or more factors in their selection of the best house. One student, with the pseudonym of Brad, designed the home shown in Figure 45.

![Figure 45. Brad’s design artifact](image)

This home, with a Trade-off Value of 186.31 (33rd percentile), consumed -2,375 kWh of energy annually with a resulting construction cost of $249,370 (which just under the cost constraint by $250,000), while meeting all specified design constraints. However, this home performed at
the 25th percentile for the human component of the house (as measured from the window-to-wall ratio). Additionally, Brad identified 3 factors for his reasoning in the Design Rationale Elicitation Task (i.e., technical, human, and economic):

“This building is completely energy efficient, has the most amount of windows, but the highest cost because of these things but the amount of energy helps to [offset] the balance.”
(Score: 3)

Experiential-Dominant trade-offs student case

Students with high Trade-off Values but low Design Rationale Elicitation scores comprise the Experiential-Dominant trade-off cluster. These 161 students were the largest cluster, and produced design artifacts that demonstrated design competency with respect to understanding how to balance competing and complementary design criteria. Their artifact Trade-off Values range from 195.28 to 252.93, which is in the 41st to 88th percentile. But students in this cluster were not likely to provide justification or cite zero trade-off factors in their selection of the best house. One student, with pseudonym Carlos, designed the home shown in Figure 46.

Figure 46. Carlos’s design artifact
This home, with a Trade-off Value of 250.38 (87th percentile) performed very well with respect to energy -9,368 kWh, and just met the construction limit of $249,443. The window-to-wall ratio as a surrogate of the human dimension of the home performed at the 50th percentile of the class. Carlos in answering the Design Rationale Elicitation Task commented on only one factor for his choice, the energy performance:

“Building 2 because it has 0 kWh and it is in between building 1 and 3.” (Score: 1)

Low dual-process trade-offs student case

Students with both low Trade-off Values and low Design Rationale Elicitation scores demonstrated low dual-process trade-offs. These 27 students, the smallest of all four clusters, produced design artifacts that did not demonstrate design competency with respect to understanding how to balance competing and complementary design criteria. Their artifact Trade-off Values ranged from 96.55 to 117.73 (1st to 5th percentile). Moreover, students in this cluster were likely to not discuss any factor in their selection of the best house. One student, with pseudonym Diana, designed the home shown in Figure 47.

Figure 47. Diana’s design artifact
This home, with a Trade-off Value of 115.17 performed really well in terms of negative energy consumption (-9,665 kWh) for a cost that was below the specified maximum ($204,084). However, the overall Trade-off Value of the home reflects the design artifact meeting only 2 of the 8 design constraints and a low attention to human trade-offs as measured through the 12th percentile of window-to-wall ratio in the class and small home size. Additionally, Diana provided a brief description of a design benefit in her choice in the Design Rationale Elicitation Task:

“Has low kWh” (Score: 1)

Discussion

The purpose of this study was twofold: first, to understand to what extent pre-engineering students understand trade-off decisions; and secondly, to understand variations in student design trade-off decisions. Results suggest that students were able to understand trade-off decisions consistent with beginning designers, and that students fit into four main patterns of their approaches in experiencing and analyzing trade-off decisions.

RQ1: To what extent do pre-engineering students understand trade-off decisions as evidenced through ability to evaluate alternative solutions by considering multiple trade-off factors?

Results of the Design Rationale Elicitation Task showed that while a quarter of the students did not cite a trade-off factor in their design alternative selection, the majority of the students were able to provide at least one reason for their choice. The finding of not citing trade-offs is consistent with research that has shown when evaluating different options, novices to not critically evaluate their design decisions (Goldstein & Hogarth, 1997). As this design experience was likely one of the first integrated design experiences for these middle school students, they are what Crismond and Adams (2012) have termed beginning designers, “students with little or no experience and no formal training in designing” (Crismond & Adams, 2012). As such, we would expect that they are not yet like informed designers who are skilled at “weighing and articulating” (Crismond & Adams, 2012, p. 761) both the pros and cons of a the design scenario. In fact, beginning designers may have a tendency to ignore or give little attention to “the unavoidable tensions and trade-offs associated with design” (Crismond & Adams, 2012, p. 761). The majority of the students (65.7%) discussed either only one or no trade-off rationale, with the technical dimension of energy the most
commonly cited dimension. Results align with previous assertions that people in general, not only students, struggle with evaluating trade-offs between two attributes of very unequal importance where the option should be “obvious” (Scholten & Sherman, 2006). By discussing only one pro or con of a design or not citing any design rationale, students are behaving in ways we would expect of beginning designers. These findings are consistent with other research in which students do not effectively make design trade-off decisions because they do not fully detail design options (Younker & McKenna, 2009), do not understand how to manage conflicting criteria (Girod et al., 2003), and fail to evaluate data pertinent to trade-offs (Fila & Purzer, 2013).

However, a notable percentage of students (28.7%) discussed two reasons for their design alternative evaluation. An even smaller number (5.6%) articulated their design rationale by discussing a comprehensive look at pros and cons of a design alternative. In other words, while the majority of students exhibited indicators of beginning designers, a notable portion of students exhibited indicators of informed designers. Previous research conducted with college students suggests students do not fully characterize their design decisions and do not reliably understand how to manage conflicting criteria (Younker & McKenna, 2009, Girod et. al, 2003) but results from this study challenges these views, and instead argues that even young students can make design trade-off decisions. These differences in findings could be because this research takes an approach to better understand the variation present in how beginning design students approach trade-offs in making design artifacts and in providing design rationale for trade-offs.

These results show promise for helping develop and encourage growth in K-16 students. These students would benefit from teaching approaches that require students give explanations for their design choices. Crismond and Adams (2012) describe two approaches used to teach decision-making to beginning designers: a reasoning-based approach which involves students making qualitative arguments (such as in the Design Rationale Elicitation Task) and a quantitative, model-based approach where students assign values and weights to factors before making a final decision (such as decision matrices). In both approaches, teachers should help scaffold students’ thinking about the trade-offs involved in a design decision, and should help student recognize both the pros and cons of design alternatives (Crismond & Adams, 2012).
RQ2: What are the patterns of design trade-off decision in pre-engineering students?

Students approach “doing” trade-offs in their design artifacts in a variety of ways, and articulate trade-offs involved in design choices differently. This research showed four patterns of variation with respect to the combination of how students experience (in the particular) and analyze (in the general) design trade-offs: High Dual-Process Trade-offs, Analytical Dominant Trade-offs, Experiential Dominant Trade-offs, Low Trade-off Demonstration. 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 and colleagues’ work with grade school students that implied young students can make trade-offs between cost and effectiveness (Purzer et al., 2013). Furthermore, these findings suggest that students can both apply relevant criteria in producing a design artifact and analyze design options, with some students doing one activity well but not the other. This finding shares similarities with prior research that highlighted students’ struggle to support design decisions with data (Cole & Mckenna, 2010; Younker & McKenna, 2009) and potential failure to evaluate data pertinent to trade-offs (Fila & Purzer, 2013) in illustrating that students might struggle with the rationale behind design decisions. However, this work proposes a new direction to more fully characterize student trade-off abilities through the Dual-Process Framework for Evaluating Student Design Trade-offs. By unpacking further variation within the beginning designers described in Crismond and Adams’ (2012) synthesis, this work adds more detail to existing knowledge of trade-offs in beginning designers through a framework to dually understand student trade-offs. Understanding the learning failures within each would allow for more meaningful future educational opportunities to help develop a more nuanced design competency.

High Dual-Process Trade-offs Cluster

The High Dual-Process Trade-offs cluster of students created design artifacts that enacted the design competency of making trade-offs in the particular case or design artifact (Trade-off Value) while also being able to reason through general domain knowledge of designs alternatives (Design Rationale Elicitation task). This cluster of students seemed to take a systems approach to how multiple competing and complementary criteria work with a systems perspective in both their own work and in evaluating the work of others from the Trade-off Value and Design Elicitation...
Task scores, respectively, and seems to be align with behavior of informed designers. Identification of this cluster of students is important in recognizing that some students “do” and “analyze” trade-offs well, and that we can differentiate these students. The dual-performance in this cluster seems to indicate deep learning of trade-offs, and suggests that this group does not seem to experience failures in connecting the abstract to the concrete or vice versa.

Students in this cluster, like Abby, are making connections to trade-offs in both the concrete sense through performance of their design artifact and through the abstract in providing rationale for their choices in a more generalized sense. If “repetitive cycles between the general and the particular” (Adams et al., 2003, p. 18) are important for developing a deep understanding of design trade-offs, then she should enforce and expand abstract and concrete knowledge of trade-offs through additional design experiences and through additional chances to abstract out in even less similar contexts.

**Analytical-Dominant Trade-offs Cluster**

The *Analytical-Dominant Trade-offs* cluster of students created design artifacts that failed to demonstrate the design competency of making trade-offs in the particular case design artifact (Trade-off Value). However, these students were able to reason through general design domain knowledge (Design Rationale Elicitation task). The identification of this cluster is important in order to better understand students’ profiles with respect to their knowledge of design trade-offs. While this cluster might not demonstrate a high competency in “doing” trade-offs, a look at how they analyze trade-offs allows a better understanding of their knowledge strengths.

Students in this cluster, like Brad, are making connections to trade-offs as a way of thinking at the abstract level but are failing to make a connection between general cases and the particular case of their design artifact performance. In order to address the learning failure of general-to-particular process in this cluster, Brad needs opportunities to continue to unpack the concept of trade-offs and apply trade-offs in additional design examples. This type of learning failure suggest that this type of student does not have the adequate knowledge structure to apply to a particular design challenge or might not have this knowledge of trade-offs structured in a way that allows for application to a particular design problem.
**Experiential-Dominant Trade-offs Cluster**

The *Experiential-Dominant Trade-offs* cluster of students created design artifacts that enacted the design competency of making trade-offs in the *particular case* design artifact (Trade-off Value). However, these students did not show definitive ability to reason through *general design domain knowledge* (Design Rationale Elicitation task). The identification of this cluster is important in order to better understand students’ profiles with respect to their knowledge of design trade-offs. While this cluster might not demonstrate in analyzing design trade-offs, they seem to excel at producing design artifacts that embody trade-offs, and a comprehensive look at their knowledge allows a more comprehensive understanding of this pattern of student.

Students in this cluster, like Carlos are almost opposite of students like Brad, and are making connections to trade-offs through the particular or concrete with their design artifact but are failing to make the abstract connection by making trade-offs that are less dependent on the particular in-class design challenge. In order to address the learning failures of particular-to-general in this cluster, Carlos needs opportunities to repack trade-offs to build his own meaning as an abstract concept and cycle through cycles of abstract to concrete. This type of learning failure suggests although the student is able to adequately address the design challenge, he is unable to integrate a generalizable approach into his existing knowledge structure.

**Low Dual-Process Trade-offs Cluster**

The *Low Dual-Process Trade-offs* cluster of students neither created design artifacts that enacted the design competency of making trade-offs in the *particular case* design artifact (Trade-off Value) nor did they demonstrate a high ability to reason through *general design domain knowledge* (Design Rationale Elicitation task). Students in this cluster, like Diana, are not making strong connections to trade-offs in either the concrete sense through performance of their design artifact or through the abstract is providing rationale for their choices in a more generalized sense, perhaps due to a lack of design experience. The Dual-Process Framework allows a differentiation between students who perform well all around, in the particular but not general or vice versa, and in cases with no experience and a resulting shallow knowledge-base. More research is needed to understand why students in this cluster are failing to exhibit knowledge of trade-offs in their
experiences or in their analyses in order to improve opportunities for students to make meaningful trade-off knowledge connections.

**Conclusion & Implications**

This chapter was intended for those interested in implementing and advancing engineering design education, particularly at the pre-college level, through an understanding of the role of evaluative judgement in students’ development. This work makes theoretical contributions, methodological contributions, and practical contributions. These implications are important for educators and administrators who are looking for impactful teaching ideas and fellow design researchers searching for empirical evidence of student variation in design thinking and design quality.

This study of over 300 middle school students makes a theoretical contribution in providing a more comprehensive picture of how students make and understand design trade-off decisions. This comprehensive understanding provides the foundation on which to shape practices towards a goal of better prepared engineers.

Design projects have the potential to help students understand important practices in engineering, such as making trade-offs. Furthermore, engineering design allows an avenue for students to begin to develop evaluative judgement as they make abstract concepts concrete through articulated decisions. This study through the *Dual-Process Framework for Evaluating Student Design Trade-offs* demonstrated the students exhibit variation in (1) how they experience trade-offs in design through their particular final design artifacts, (2) how they analyze design trade-offs through more abstract examples of design alternatives. If an understanding of design trade-offs consists of two parts, then it is important to understand both pieces of the puzzle. This study provides a methodological contribution through this framework.

The practical implications from this study center on a guide to noticing students. Particularly in the K-12 setting in which developing an understanding of trade-offs is central to science education, a more comprehensive look at students’ abilities to make trade-offs would allow teachers to understand both where learning failures are taking place and where trade-off connections are happening. As teachers are better able to anticipate student needs they can begin to develop more effective and targeted learning experiences that encourage students to build more
connections not only between design trade-offs but also between design and other disciplinary (e.g. sciences) areas.

**Limitations & Future Work**

In order for multimodal research to be conducted rigorously and with meaning to the community, quality considerations are especially important. In particular, validity and reliability are important in data collection, data analysis and interpretations unique to a multimodal approach. This study took an approach to ensure an ecologically valid data collection and thorough analysis. Yet, there were a few limitations in the study related to research quality.

First, the findings of this study can only be generalized to student populations similar to the sample used in this study using Energy3D or similar design experiences. This group of students, based on school demographics and my classroom observations had ample resources in terms of engaged and competent teachers and technological resources. Although the science teachers in the school collaborated extensively to integrate curriculum, students had few formal engineering design experiences. They had taken part in small design activities as part of their previous science learning. Furthermore, the classroom instruction did not explicitly ask students to make design trade-offs nor give explicit instruction in making evaluative design judgements. These student characteristics and research design with lack of explicit instruction in trade-offs should be considered when using findings of this study to inform implementation of similar engineering design projects in the K-12 classroom. However, in analyzing over 300 students’ this analysis is robust in terms of providing a cluster analysis with ample number of samples. In order to address theoretical validation, which “implies a continuous focus on the question of whether the theories or the knowledge produced appropriately correspond to the empirical reality observed” (Walther, Sochacka, & Kellam, 2013, p. 641), I collected data in the students’ natural school setting in an authentic task that enables the reality because it requires trade-offs.

Second, this study took a two-prong approach to understand design trade-off student profiles through design artifact and design rationale. As such, I needed to quantify qualitative data. Limitations for the Trade-off Value method are discussed in the previous chapter. In analyzing student responses to the Design Rationale Elicitation task, I took an etic approach, grounded in the definition of design (Asimow, 1962). In coding student responses, I and a second researcher independently coded and maintained a high degree of agreement.
Further research should investigate the extent to which repeated exposure to design projects and elicitation of design evaluations develops students’ design thinking, and resulting relationship to design product quality. This study provided two snapshots into students’ ability to make trade-offs in the particular case and general design domain knowledge. Repeated exposure to design projects might allow deeper learning as students oscillate between breaking down and building back up the concept of trade-offs. As engineering design provides opportunities for integrated learning, future work should also investigate differences in engineering science learning between the student clusters.
CHAPTER 5. SUMMARY, IMPLICATIONS AND FUTURE RESEARCH DIRECTIONS

Overview

In the three studies of this dissertation, I work towards a theory-generating contribution regarding the development of trade-off decisions in the pre-engineering student designer through the following objectives:

1. Develop a conceptual understanding of students’ priority of and understanding of the term *trade-offs* in design
2. Explore how students perform trade-offs in design and how this performance can be measured in a systematic, easy way that encompasses multiple competing and conflicting criteria and reflects competent design
3. Understand how pre-engineering students explain trade-offs in design
4. Explore patterns of how students dually perform and explain design trade-off decisions

In this final chapter I begin with a succinct summary of the motivation for studying pre-engineering designer trade-offs before providing a summary of each individual study. Then, I integrate findings from each preceding chapter through a “conversation” between the chapters. Next, I present implications for researchers, educators, students and policy. Finally, I conclude this chapter with directions for future research and closing acknowledgements.

Design trade-offs are an important educational and research focus

Design is the distinguishing activity of engineering (Dym, 1994; Dym et al., 2005) and because design is so critical to the engineering profession, it is a core focus in engineering education at the college level (Atman, Eris, McDonnell, Cardella, & Borgford-Parnell, 2014). Additionally, engineering education at the K-12 level also emphasizes design as a key practice and a disciplinary core idea in engineering in the Next Generation Science Standards (NGSS) (Achieve, 2013). Hence, design has become an educational focus for all regardless of whether they pursue engineering or not.

Design is described as a series of decisions (Ullman, 2001) with inevitable trade-off decisions (Wong et al., 2009) which are often the most crucial and most impactful decisions in
engineering (National Research Council, 2001). Students’ abilities to make trade-off decisions are important for undergraduate engineers (ABET, 2014) as a “fundamental construct” (Chen et al., 2006) and important even earlier for K-12 students as a “core concept of technology” (ITEEA, 2007), and as a disciplinary core idea linking science knowledge and design knowledge in national standards (Achieve, 2013). Research in design trade-offs is crucial in advancing theory that can help to prepare K-12 with exceptional decision-making skills.

**Chapter summaries**

Each chapter of the three studies in this dissertation provides unique insights on students’ conceptions, performance, and explanations of trade-off decisions and the patterns of variation among these parameters, as show in Figure 48. Insights combined from each of the three studies better informs the overall depiction of student designer trade-off decisions.

![Figure 48. Summary of three studies](image)

**Study 1: Prioritizing Trade-offs**

The first study investigates how students describe and prioritize design trade-off decisions through the following research questions: Do students report changes in their perceived importance of making-trade-offs after a design project, and if so, how do their conceptions change?
A McNemar test was used to statistically analyze pre-post changes on a Conceptions of Design Test. I found that significantly fewer students ranked trade-offs to be a least important design activity (n=746). In a qualitative thematic analysis of open-responses where students explain their ranking, I found many students did not understand either the concept or the terminology of “trade-offs”, despite the relevance of making tradeoffs to practicing designers and the use of “trade-offs” in the Next Generation Science Standards (Achieve, 2013). Per the NGSS, middle school students should be able to evaluate solutions with respect to how well they meet criteria and constraints to systematically understand why features in a particular design solution might perform “best” (Achieve, 2013, ETS1.C). The findings from this study suggest that there might be disconnect from what students are supposed to be able to do and their understanding of the meaning and importance of this particular design activity. 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 on the role of trade-offs in design and how to manage trade-offs, students may struggle with linking intuitive trade-off decision-making with the terminology of “balancing trade-offs” that references an explicit design strategy.

**Study 2: Enacting Trade-offs**

The second study seeks to understand and measure how students “do” trade-offs in design. Central to this study was developing a way to depict design artifact quality that: (1) encompasses multiple complementary and competing dimension, (2) can be applied easily and systematically and consistently, and (3) is indicative of design competency. I developed the Trade-off Value protocol which assesses design artifacts in the areas of human, technical, and economic factors. The Trade-off Value is calculated as the sum of percentile ranks of student performance relative to their peers. I analyzed approximately 400 student design artifacts to test the Trade-off Value protocol and calculated Trade-off Value scores for each design to investigate patterns of variation in the quality of students’ artifacts. Results suggest the Trade-off Value Protocol is a useful tool for three reasons. First, because it is conceptually grounded in the definition of design as embodying trade-offs (Asimow, 1962), it provides a comprehensive way to think about the interaction of client/user priorities, design possibilities and objective measures. Second, the protocol while being systematic is also easy to use. Third, the Trade-off Value protocol represents an important feature of design competency with which beginning designers struggle, and is useful
in revealing variations in design competency. In addition, using an etic approach to thematic analysis of student design artifacts, I identified five distinct patterns of variation in artifact quality which suggests patterns in ways students address multiple complementary and conflicting design dimensions that indicates variations in design trade-off competency. These five patterns: negative energy consumption goal, minimize construction costs, maximize aesthetics through large windows, disregard for livability, and balanced trade-offs, further elaborate on the variation of beginning designers with respect to making trade-offs. The first four patterns align well with Crismond and Adams’ (2012) synthesis that beginning designers are apt to cite only a pro to the chosen design or a con of a passed over design such as referencing high cost as a negative aspect of a design or energy efficiency as a positive aspect. These five patterns build on current research on how students discuss design decisions by suggesting beginning designers might also approach the design process by paying attention to only one aspect of a design. However, the variation of design artifact performance as evidenced from the five patterns results of this study suggest that some students might approach design in a way more consistent with informed designers by being mindful of the inevitable tensions and trade-offs when producing a design artifact.

**Study 3: Reasoning about Trade-offs**

The third study provides a look at how students explain trade-offs in design and the relationship between how students “do” and explain design trade-offs. Through the context of an in-class individual design challenge, I collected data from 318 middle school students including (1) the final design products, and (2) a post-challenge design reasoning elicitation problem. I characterized patterns of student trade-offs through the *Dual-Process Framework for Evaluating Student Design Trade-offs*. The analysis started with the calculation of artifact quality score (called Trade-off Value) for each student and the scoring of the design reasoning elicitation problem through a content analysis of student responses. I used a cluster analysis to identify groups exhibiting distinct patterns of trade-offs as evidenced from these two scores. Results suggest that students were able to understand trade-off decisions consistent with beginning designers, and that students fit into four main patterns of their approaches in experiencing and analyzing trade-off decisions. These four patterns, high dual-process trade-offs, low dual-process trade-offs, analytical-dominant trade-offs, experiential-dominant trade-offs, begin to unpack the variation in behavior of beginning designers (Crismond & Adams, 2012). In summarizing studies of beginning
designers Crismond and Adams (2012) emphasize that beginning designers do not 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). This dissertation builds on Crismond and Adams’ (2012) synthesis through suggesting variation in the dual-way that students enact trade-offs (as evidenced by their design artifact) and analyze trade-offs (as evidenced from a rationale eliciting prompt). Some students might enact trade-offs consistent with informed designers or in a more naïve way and similarly, some student might analyze trade-offs more consistent with informed designers or in a more naïve way. Findings may be used by educators and researchers to understand variation in students’ trade-off profiles that might affect deeper learning.

“Conversations” between chapters

Through these three studies, I analyzed over 1,100 middle school students engaged in engineering design in order to understand their trade-off decisions from multiple perspectives. While findings from each paper highlight an element of trade-offs, the interaction of these three papers allows a layered understanding of student designers’ trade-offs. If Paper 1 could talk to Paper 2 it would suggest that students have difficulty articulating trade-offs in design through design language. Paper 1 would suggest that we need another way to get at students’ understanding of trade-offs and would suggest that in order to develop a more comprehensive perspective of student trade-offs we look into how students “do” trade-offs.

Paper 2 first developed a meaningful protocol to assess the value or comprehensive quality of student designs. Through this protocol, this paper demonstrated that we can assess the degree to which students are able to produce designs that embody trade-offs. But Paper 2 understands that while asking students to “show me how you make trade-offs” allows one lens into student knowledge of trade-offs, another way to get at students understanding is to ask “tell me how you make trade-offs.” Paper 3 builds on findings from Papers 1 and 2 for an exploration and deeper understanding of the combined experiential and analytical aspects of trade-offs.

Contribution

There are few studies on how students are taught to make engineering design decisions (Jonassen, 2012), let alone the specific subset of trade-off decisions in a K-12 setting. Moreover, understanding the connection between student decisions and quality of their work is under
researched (Tai et al., 2017). Due to the nature of research methodologies, prior studies investigating K-12 student decision-making (e.g. Brotman et al., 2010, Papadouris, 2012a, Schkade & Payne, 1994) typically explore small numbers of cases, limiting the ability to examine variation within this beginning designer group. The research approach in this dissertation is creative and original because it uses learning analytics, an emerging area of research (Macfadyen et al., 2014), with more conventional data (e.g. tests and reflections) with a large dataset, allowing a more comprehensive picture of the student design process.

Taken together, the results from the three inter-related studies from this dissertation with over 1,000 students highlight the variation of pre-engineering students’ design trade-offs with respect to how students value, understand the language of, enact performance of, and provide their reasoning in order to start building a theory of trade-offs in student designers. This comprehensive understanding provides the foundation on which to shape practices towards a goal of better prepared engineers.

These studies align with previous assertions that people in general, not only students, struggle with evaluating trade-offs between two attributes of very unequal importance where the option should be “obvious” (Scholten & Sherman, 2006). Previous research conducted with college students suggests students do not fully characterize their design decisions and do not reliably understand how to manage conflicting criteria (Younker & McKenna, 2009, Girod et. al, 2003) but my dissertation challenges these views, and instead argues that even young students can do these activities. These differences in findings could be because this research takes an approach to better understand the variation present in how beginning design students approach trade-offs in making design artifacts and in providing design rationale for trade-offs. In particular, results from Study 2 suggest that middle school students exhibit varying patterns of making trade-offs through their design artifacts. 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 and colleagues’ work with grade school students that implied young students can make trade-offs between cost and effectiveness (Purzer et al., 2013). Furthermore, Study 3 argues that students can both apply relevant criteria in producing a design artifact and analyze design options, with some students doing one activity well but not the other. This finding shares similarities with prior research that highlighted students’ struggle to support design decisions with data (Cole & Mckenna, 2010;
Younker & McKenna, 2009) and potential failure to evaluate data pertinent to trade-offs (Fila & Purzer, 2013) in illustrating that students might struggle with the rationale behind design decisions. However, this work differs in that Study 3 suggests a new direction to more fully characterize student trade-off abilities through the Dual-Process Framework for Evaluating Student Design Trade-offs. By unpacking further variation within the beginning designers described in Crismond and Adams’ (2012) synthesis, this work adds more detail to existing knowledge of trade-offs in beginning designers through a framework to dually understand student trade-offs.

**Implications:** The value of characterizing student design trade-off decisions in engineering education

My dissertation makes contributions in five areas: Methodological, implications for design researchers, implications for pre-college engineering & engineering educators, suggestions for beginning designers, and a need for policy introspection. This dissertation has methodological implications as student learning and development is a very complex topic. As such, I have used multiple methods of data collection and multiple ways to analyze data in order to paint a more comprehensive picture of trade-offs in the student designer. This study, in investigating over 1,000 students’ design artifacts, design rationales, and conceptions of trade-offs, is novel from both the types and magnitude of data. The number of students was necessary to start building a theory of trade-offs in student designers through a look at patterns. I will continue to test the Trade-off Value protocol in similar design challenges but with different types of students (different pre-college and college ages, school-makeup, etc.) and will test with design challenges outside of the Energy3D platform in order to understand the utility of the Trade-off protocol and the generalizability of the patterns of trade-offs illuminated in this dissertation.

Related to methodological implications, this study has 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 quality and various design behaviors and cognition. Moreover, because the Trade-off Value is relative easy to use and can be applied systematically it allows scaling up studies to larger numbers of students in order to investigate more generalizable patterns.
It is important to prepare and familiarize 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. First, students might not understand the design language that educators use in the classroom as students bring their own associations with design terminology with them to projects. It is important to be cognizant of how we as educators use our design language (or jargon), and to continually check in our students’ comprehension and our own expectations of students’ knowing. The Trade-off Value protocol is useful for design educators from two perspectives. First, it is useful as a summative assessment to evaluate student artifacts. Second, the Trade-off Value has potential utility as a formative tool as it allows both a comprehensive assessment of overall quality while allowing understand of how well a design performs with respect to the key areas of design value: human, technical, and economic dimensions. This tool has the potential to facilitate design conversations to scaffold the important work of design trade-off decisions for students. Finally, an understanding of the Dual-Process Framework for Evaluating Student Design Trade-offs allows a structure for teachers to both assess and help build students’ design skills in trade-offs. Although a final product is the default in engineering design assessment, it is only a part of the puzzle. In order to more fully understand students’ trade-off knowledge we need to better understand both how they experience trade-offs and how they analyze trade-offs. Encouraging students to “do” trade-offs in their designs and provide rationale for design decisions could more fully develop their knowledge in this space.

Implications for students are quite straightforward. Trade-offs are an important part of the work of practicing designers and engineers. As such, they need to be able to make trade-offs. Moreover, these studies showed that even very beginning designers are capable of demonstrating trade-off abilities. Global challenges such as energy shortages, clean water needs, emerging diseases, and climate change will require innovative solutions informed by engineering design content and conceptions. The ability of students to understand what is involved in high quality design solutions is important in their future contributions to attack such global challenges.

This dissertation would be remiss in only looking at implications for students, educators, and researchers in light of current integrated STEM policy in the United States. The National Academy of Engineering reports such as Engineering in K-12 education: Understanding the status and improving the prospects (National Research Council, 2009) and A Framework for K-12
Science Education, (National Research Council, 2012) state the need for integrated science and engineering learning in precollege settings. In order to address this need, Next Generation Science Standards (NGSS) (Achieve, 2013) were developed to link science and engineering practices with disciplinary core ideas. Engineering design is being included as a part of STEM education throughout primary and secondary grades. States that adopted NGSS specify that students should demonstrate an understanding of engineering design through the science and engineering practices, disciplinary core ideas, and crosscutting concepts. This study shows the need to take a step back from policy making and implementation to better understand gaps in student conceptions and understanding of key design behaviors such as making trade-offs. This level of understanding is critical so that teaching efforts start from an understanding of what students currently do and know in order to address opportunities to encourage important student growth in not only the direction of engineering design but more importantly as contributors in innovating through global challenges.

Future Work

The results of this three-paper dissertation show that students have various levels of understanding of trade-offs. Analysis of design artifacts embody how students practice trade-offs while, investigating the degree to which students reason about trade-offs show patterns of variation between in reasoning and abilities to make trade-off decision in design. These three studies of student trade-offs in my dissertation are first steps. Each study leaves room for future work, as discussed in more detail in each of the respective chapters. These three papers are set within the context of the Energy3D platform. As such, I am able to use findings from each of the studies to speak to each other. However, I cannot make generalizations to other contexts. My entire dissertation in this layered approach, provides the foundation to keep learning more about design trade-offs in pre-engineering students. Future work that could further illuminate this important design behavior in students could include modelling additional parameters of student design trade-offs (such as including design actions, additional measures of design conceptions, and content knowledge tests) in order to develop a latent typology in order to further define exclusive and exhaustive types of trade-offs in student designers.
Closing Acknowledgements

Thank you to the creative and engaged 1,000+ middle school students who participated in this study and the eleven dedicated teachers who guided their efforts. I hope that the understanding we develop of their design competencies will help impact the educational efforts of the next generation of engineering and pre-engineering students!
REFERENCES


Student Assent Form

Study: Learning Engineering Design Using a CAD Tool

Investigators: Dr. Senay Purzer, Dr. Robin Adams, Molly Goldstein

During the school year you are going to be completing some hands-on activities related to science technology and engineering. We are conducting a research project through Purdue University to understand how useful these hands-on activities are for students to learn about science and engineering.

We will ask all students to complete short surveys before and after working with the hands-on activities. These surveys will include questions about previous experiences as well as demographics information. We will ask some students to participate in follow-up talks to learn about your experiences using the software. This interview will be completely optional, and will take place in your classroom during one class period. The hands-on activity uses a CAD system that collects data as you make designs.

We will also be taking pictures of the classroom. If you do not want your photo included in any materials, we will not take your photos.

Participation in this study is optional. You can agree to be in the study now and change your mind later. If you choose not to participate, we will not use information about you in our research. Whether or not you participate will not affect your grades or experiences in your class. The records of this study will be kept private. In any sort of report we publish, we would not include any information that will make it possible to identify you. Only the Purdue Research Team will have access to any data. We will keep data for at least 3 years after the study is complete, and we will follow steps to keep all data private.

This study will take about 2 weeks, and will be for about an hour each day over those 2 weeks during class.

You can ask any questions that you have about this study. If you have a question later that you didn't think of now, you can ask me next time.

Signing here means that you have read this paper or had it read to you and that you are willing to be in this study. If you don’t want to be in this study, don’t sign. Remember, being in this study is up to you, and no one will be mad at you if you don’t sign this or even if you change your mind later.

Your name______________________________

Date__________________

Signature of Person Explaining Study__________________________
Formulario de Consentimiento del Estudiante

Estudio: Aprender Diseño Ingeniería Utilizar una herramienta de CAD

Investigadores: Dr. Senay Purzer, Dr. Robin Adams, Molly Goldstein

Durante el año escolar que va a ser completar algunas actividades prácticas relacionadas con la tecnología de la ciencia y la ingeniería. Estamos llevando a cabo un proyecto de investigación a través de la Universidad de Purdue para entender ¿Qué utilidad tienen estas actividades prácticas para que los estudiantes aprendan sobre la ciencia y la ingeniería.

Pediremos a todos los estudiantes para completar encuestas cortas antes y después de trabajar con las actividades prácticas. Estas encuestas incluyen preguntas sobre las experiencias anteriores, así como la información demográfica. Le pediremos a algunos estudiantes a participar en las conversaciones de seguimiento para aprender acerca de sus experiencias en el uso del software. Esta entrevista será completamente opcional, y tendrá lugar en el salón de clase durante un período de clase. La actividad práctica utiliza un sistema de CAD que recoge datos como hacer diseños.

También vamos a tomar fotos de la sala de clases. Si usted no desea que su foto incluida en cualquier material, no vamos a tomar sus fotos.

La participación en este estudio es opcional. Puede acepta participar en el estudio ahora y cambiar de opinión más tarde. Si usted decide no participar, no vamos a utilizar la información sobre usted en nuestra investigación. Sea o no participar no afectará sus calificaciones o experiencias en su clase. Los registros de este estudio serán confidenciales. En cualquier tipo de informe que publicamos, no estaríamos incluir cualquier información que permita identificarle. Sólo el equipo de investigación de Purdue tendrá acceso a ningún dato. Vamos a mantener los datos durante al menos 3 años después de que el estudio se ha completado, y vamos a seguir los pasos para mantener todos los datos privados. Este estudio se llevará a cerca de 2 semanas, y será por alrededor de una hora cada día durante esas 2 semanas durante la clase. Usted puede hacer cualquier pregunta que usted tenga acerca de este estudio. Si usted tiene una pregunta más adelante que usted no pensó de ahora, usted puede preguntarme la próxima vez. Firma aquí significa que ha leído este documento o tenía que leer para usted y que usted está dispuesto a participar en este estudio. Si usted no desea participar en este estudio, no firme. Recuerda, en este estudio es de usted, y nadie se enojará si usted no firma esta o incluso si cambia de opinión más adelante.

Su nombre_____________________________________

Fecha__________________

Firma de la persona Estudio Explicando________________________
Parent Informational Packet

Study: Learning Engineering Design Using a CAD Tool

Investigators: Dr. Senay Purzer, Dr. Robin Adams, Molly Goldstein

Dear Parent:

During the school year your child is going to be completing some hands-on activities related to science and engineering in his or her science or technology classroom. These new activities are designed to teach your child science, engineering and technology. Your child will work on real-world problems such as designing energy efficient buildings using a computer-aided design software. This project is funded by the National Science Foundation and our research will help explain how students learn and apply science concepts when solving real-world problems. Your child is being asked to participate because the new hands-on activities are taking place in his/her classroom.

Participation in this research is optional. If you agree to have your child participate, this study will take place for about one hour a day over two weeks during class time. Your child will not miss out on school or class time because the class will all be using the same hands-on activity.

If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact Senay Purzer at 765-496-1684 or by email spurzer@purdue.edu.

Enclosed is a parent consent form and child assent form. Please sign, date and return the forms with your child. The research team is providing a drop-box in the classroom for students to leave the forms. Thank you for reading the enclosed materials. We look forward to working with your child.

Sincerely,

Senay Purzer
Associate Professor
spurzer@purdue.edu
Parent Consent Form

Study: Learning Engineering Design Using a CAD Tool

Investigators: Dr. Senay Purzer, Dr. Robin Adams, Molly Goldstein

Dear Parent:

During the school year your child is going to be completing some hands-on activities related to science and engineering in his or her science or technology classroom. These new activities are designed to teach your child science, engineering and technology. Your child will work on real-world problems such as designing energy efficient buildings using a computer-aided design software. This project is funded by the National Science Foundation and our research will help explain how students learn and apply science concepts when solving real-world problems. Your child is being asked to participate because the new hands-on activities are taking place in his/her classroom. We will be closely working with your child’s science or technology teacher and around 9,000 other students over 4-5 years.

What will I do if I choose to let my child to be in this study? Participation in this research is optional. If you agree to have your child participate, we will be tracking his/her progress by looking at the work that he/she does in these new activities. We will have all students complete a survey before and after working with the software. The survey will include questions such as previous design experience as well as demographics information. We may also ask children questions about their design projects and take pictures of the classroom layout. If your child is selected to participate in a follow-up interview, the interview will be completely voluntary, will take place during one class period and will be in the classroom. Additionally, we will take photos of the class for research and publication purposes. We would greatly appreciate your child’s participation in the study as it will inform activities for future projects.

How long will my child be in the study? The study will take place in your child’s classroom and will last for approximately two weeks, for about one hour per day.

What are the possible risks or discomforts? Your decision whether or not to participate will not affect your child’s grades or experiences in their science and/or technology class. Although there is always a risk of breach of confidential data, the Purdue Research Team will take steps to minimize any such risk. The project’s research records may be inspected by the Purdue University Institutional Review Board or its designees to ensure that participants’ rights are being protected.

Are there any potential benefits? There are no potential benefits to participating but we expect your child will learn science and engineering and how to use a computer-aided design software.

Will information about my child and his/her participation be kept confidential? The project’s research records may be reviewed by the National Science Foundation, Office for
Formulario de Consentimiento de los Padres

**Estudio:** Aprender Diseño Ingeniería Utilizar una herramienta de CAD

**Investigadores:** Dr. Senay Purzer, Dr. Robin Adams, Molly Goldstein

Estimado padre de familia:

Durante el año escolar de su hijo se va a completar algunas actividades prácticas relacionadas con la ciencia y la ingeniería en su escuela o la tecnología en las aulas. Estas nuevas actividades están diseñadas para enseñar a su hijo la ciencia, la ingeniería y la tecnología. Su hijo trabajará en problemas del mundo real, tales como el diseño de edificios energéticamente eficientes utilizando un software de diseño asistido por ordenador. Este proyecto está financiado por la Fundación Nacional de la Ciencia y de nuestra investigación ayudará a explicar cómo los estudiantes aprenden y aplican conceptos de la ciencia en la resolución de problemas del mundo real. Se le pedirá a su hijo a participar porque las nuevas actividades prácticas se llevan a cabo en su / su salón de clases. Vamos a trabajar estrechamente con la ciencia o la tecnología de la maestra de su niño y alrededor de 9,000 otros estudiantes mayores de 4-5 años.

¿Qué voy a hacer si yo elijo dejar que mi hijo participe en este estudio? La participación en esta investigación es opcional. Si usted acepta que su hijo participe, estaremos rastreando su/ su progreso al ver el trabajo que él/ella hace en estas nuevas actividades. Tendremos todos los estudiantes completar una encuesta antes y después de trabajar con el software. La encuesta incluirá preguntas como experiencia en el diseño anterior, así como la información demográfica. También podemos pedir a los niños sobre sus proyectos de diseño y tomar fotos de la disposición del aula. Si su niño es seleccionado para participar en una entrevista de seguimiento, la entrevista será completamente voluntaria, se llevará a cabo durante un período de clase y estará en el salón de clases. Además, vamos a tomar fotos de la clase con fines de investigación y de publicación. Agradeceríamos mucho la participación de su hijo en el estudio, ya que informará a las actividades para los proyectos futuros.

¿Cuánto tiempo estará mi hijo en el estudio? El estudio se llevará a cabo en el aula de su hijo y tendrá una duración de aproximadamente dos semanas, durante aproximadamente una hora por día.

¿Cuáles son los posibles riesgos o molestias? Su decisión de si debe o no participar no afectará las calificaciones o experiencias de su hijo en su ciencia y/o tecnología de clase. Aunque siempre hay un riesgo de vulneración de datos confidenciales, el equipo de investigación de Purdue se toman medidas para reducir al mínimo cualquier riesgo. Registros de la investigación del proyecto pueden ser inspeccionados por la Junta de Revisión Institucional de la Universidad de Purdue o sus designados para asegurar que los derechos de los participantes están siendo protegidos.

¿Hay beneficios potenciales? No existen beneficios potenciales a participar, pero esperamos que su hijo aprenderá la ciencia y la ingeniería y la forma de utilizar un software de diseño asistido por ordenador.
APPENDIX B. CLUSTER ANALYSIS

Technical Report for Cluster Analysis Quality & Reflection

Molly Goldstein
Last update: March 13, 2018

Data

- 2017 Spring, Clay Middle School
  - 318 Students, 3 Teachers
  - Project: Net-Zero Energy Home
- 2017 Spring, Eggers Middle School
  - 80 Students, 1 teacher (5 sections)
  - Project: Net-Zero Energy Home

Key Variables

- Trade-Off Value: measure of design quality, scale of 0-400
- Design rationale: open-ended question that has been coded for levels 0 - 3
- Density: cumulative count of all actions divided by duration

Procedures & Results

1. Descriptive analysis of key variables

<table>
<thead>
<tr>
<th>Statistics</th>
<th>EMS Tradeoff Value (0-400)</th>
<th>EMS Design Rationale (0-4)</th>
<th>CLMS Tradeoff Value (0-400)</th>
<th>CLMS Design Rationale (0-4)</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>196.25</td>
<td>.60</td>
<td>204.24</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>S.D.</td>
<td>44.74</td>
<td>.67</td>
<td>42.32</td>
<td>.84</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>288.72</td>
<td>3</td>
<td>310.84</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>71.57</td>
<td>0</td>
<td>81.25</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>217.15</td>
<td>3</td>
<td>229.59</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>196.57</td>
<td>1</td>
<td>208.91</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>171.07</td>
<td>0</td>
<td>181.25</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td>232.36</td>
<td>1</td>
<td>237.12</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Skewness</td>
<td>-.62</td>
<td>.93</td>
<td>-.48</td>
<td>.19</td>
<td></td>
</tr>
<tr>
<td>Kurtosis</td>
<td>.43</td>
<td>.90</td>
<td>-.22</td>
<td>-.71</td>
<td></td>
</tr>
</tbody>
</table>
1. Correlations among Key Process Variables and Outcome Variables (Trade-off Value & Rationale)

EMS: $r = 0.133, n = 80, p = 0.12$
CLMS: $r = 0.108, n = 318, p = 0.05$

2. Hierarchical Clustering

The dataset consisted of 318 cases with two features (trade-off value and rationale). I performed hierarchical agglomerative clustering using the Ward’s method for cluster distance in SPSS. I visually inspected the cluster dendrogram, and saw that cluster distance substantially reduced under a height of 10, which would result in 2 clusters, and a height of 5, which would result in 4 clusters. In order to allow for discernable variation between clusters, I determined that 4 clusters would be an appropriate number of clusters for analysis.

3. K-means Clustering

K-means clustering is an appropriate clustering method when the number of clusters can be assumed based on knowledge of underlying theory or of prior results. While I assumed that 4 clusters of students might exist from the data:
• H\_Trade-off Value, H\_Rationale,
• H\_Trade-off Value, L\_Rationale
• L\_Trade-off Value, H\_Rationale
• L\_Trade-off Value, L\_Rationale

(where H= high, L = low)

The prior Hierarchical Clustering approach also supports the total cluster count to four. I calculated the size and descriptives of the clusters using K-mean clustering technique in SPSS.

**Size and Vector of Clusters**

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Size</th>
<th>Trade-off Value</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>94</td>
<td>153.96</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>310.84</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>161</td>
<td>231.25</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>81.25</td>
<td>1</td>
</tr>
</tbody>
</table>
ANOVA of Effect of Cluster Membership on Trade-off Value and Rationale

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>p-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade-off Value</td>
<td>637.23</td>
<td>0.000</td>
</tr>
<tr>
<td>Rationale</td>
<td>3.61</td>
<td>0.014</td>
</tr>
</tbody>
</table>
APPENDIX C. IJEE REPRINT RIGHTS

IJEE3583: Investigating Middle-School Students’ Conceptions of Trade-offs in Design -- reprinting in your dissertation excerpts the paper

Ahmad Ibrahim <ahmad_1101@bell.net>
To: Molly Hathaway Goldstein <molly.hathaway@gmail.com>
Thu, May 24, 2018 at 4:02 PM

Good afternoon,

Thank you for your e-mail.

Please feel free to reprint in your dissertation any parts from your paper: Investigating Middle-School Students’ Conceptions of Trade-offs in Design.

My best wishes,

Ahmad Ibrahim

---

From: Molly Hathaway Goldstein <molly.hathaway@gmail.com>
Sent: Thursday, 24 May, 2018 4:38 PM
To: Ahmad Ibrahim <ahmad_1101@bell.net>
Subject: Re: IJEE3583: Investigating Middle-School Students’ Conceptions of Trade-offs in Design (proofs; 10 pages)

Dr. Ibrahim,

I am completing a doctoral dissertation at Purdue University entitled Characterizing Trade-off Decisions in Student Designers. I would like your permission to reprint in my dissertation excerpts from IJEE3583 Investigating Middle-School Students’ Conceptions of Trade-offs in Design*. Please let me know if you would like any additional information.

Best Regards,

Molly Goldstein

---

On Sat, Feb 24, 2018 at 9:54 AM, Molly Hathaway Goldstein <molly.hathaway@gmail.com> wrote:

Dr. Ibrahim,
Investigating Middle-School Students’ Conceptions of Trade-offs in Design*

MOLLY H. GOLDSTEIN
School of Engineering Education, Purdue University, Wang Hall, 3rd Floor, 516 Northwestern Avenue, West Lafayette, Indiana, 47906, USA. E-mail: goldstein@purdue.edu

ROBIN S. ADAMS
School of Engineering Education, Purdue University, Wang Hall, 4th Floor, 516 Northwestern Avenue, West Lafayette, Indiana, 47906, USA. E-mail: rsadams@purdue.edu

SENAY PURZER
School of Engineering Education, Purdue University, Wang Hall, Room 4565, 516 Northwestern Avenue, West Lafayette, Indiana, 47906, USA. E-mail: purzer@purdue.edu

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 us 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-
VITA

Molly Hathaway Goldstein

School of Engineering Education, Purdue University
516 Northwestern Avenue, WANG 3500, West Lafayette, IN 47906

goldstm@purdue.edu
http://web.ics.purdue.edu/~goldstm

EDUCATION

Ph.D. Engineering Education, Purdue University, West Lafayette, IN
May 2018
Dissertation: Characterizing Trade-off Decisions in Student Designers
Advisors: Dr. Şenay Purzer and Dr. Robin Adams, Purdue University School of Engineering Education

M.S. Systems and Entrepreneurial Engineering, University of Illinois, Urbana-Champaign, IL
May 2006
Thesis Title: Decision Analysis: The Under-advised Group in Prenatal Diagnostics
Advisor: Dr. Ali Abbas

B.S. General Engineering, University of Illinois, Urbana-Champaign, IL
August 2004

HONORS & AWARDS

Purdue College of Engineering Outstanding Research Award
Spring 2017
Bilsland Dissertation Fellowship, Purdue University Graduate School
Fall 2017-
Spring 2018
Purdue College of Engineering Outstanding Service Award
Spring 2016
Purdue Graduate Student Government Travel Grant

Spring 2015,
Fall 2016

Purdue Engineering Education Exploration Fellowship

Fall 2013
List of Teachers Ranked as Excellent by their Students, University of Illinois

Spring 2005,

Fall 2004,
Spring 2005,
Fall 2005,
Spring 2006

Tau Beta Pi, Engineering Honor Society inductee, University of Illinois

2003

**Research Experience**

**Graduate Research Assistant**, Design Thinking with Large Data, Purdue University,
2013-

NSF Project: Collaborative Research: Large-Scale Research on Engineering Design Based on Big Learner Data Logged by a CAD Tool (DUE 1348547)

Supervisors: Dr. Şenay Purzer and Dr. Robin Adams

Research work seeks to understand the student design process in conjunction with student conceptions of design (i.e. what they do and what they think). Learning analytics, traditional tests and reflections will be used to group students based on the patterns they exhibit related to decision-making. My rationale is that identifying these patterns will help K-16 educators (1) understand students’ starting points in decision-making and (2) incorporate appropriate design activities into their curricula. I postulate that differentiated design decision-making patterns will arise between and within student age groups (i.e. middle school, grade 9, grades 10-11, grade 12-undergraduates).

**Graduate Research Assistant**, Entrepreneurial Case Studies, University of Illinois
2005-2006

Supervisor: Dr. Larry Schook

- Performed research within university personnel to find the most significant contributions in faculty ventures
- Corresponded with, scheduled, and interviewed potential case subjects
- Conducted semi-structured interviews with faculty regarding their technology transfer projects
- Co-authored case studies for instructional use and publication based on interviews
Graduate Research Assistant, University of Illinois
Summer 2004
Supervisor: Dr. Raymond Price

- Performed literature review for Human Behavior in Engineering
- Created annotated bibliography of technical visionaries

TEACHING AND ADVISING EXPERIENCE

Purdue University – School of Engineering Education
Faculty Apprentice for Graduate level course: History & Philosophy of Engineering Education
Spring 2016
with Dr. Robin Adams & Dr. Brent Jesiek

- Co-taught graduate level in the history and philosophy of engineering education through tools and frameworks to guide critical reflection and analysis of philosophical, epistemological, and historical arguments
- Participated in syllabus design, preparing and facilitating classroom activities and in-class discussions, and grading assignments

University of Illinois – School of Industrial & Enterprise Systems Engineering
Graduate Teaching Assistant for Engineering Graphics
2004-2006

- Taught hand-sketching and computer modeling labs
- Evaluated student performance and progress by grading homework, quizzes, exams, and design projects
- Achieved Campus Teaching Award each semester, based upon student evaluations

University of Illinois – School of Industrial & Enterprise Systems Engineering
Graduate Teaching Assistant for Capstone Design
2006

- Supervised 32 industry-sponsored projects from plant layout redesign to measuring and analyzing design changes of a treadmill
- Evaluated economic analyses of the projects, answering group questions concerning payback periods and time value of money

University of Illinois – Department of Animal Sciences
Graduate Teaching Assistant for ANSC592: Creating Value in the Life Sciences: Defining Roles and Roadmaps for the Entrepreneur
2005

- Co-Developed and originated new course content, syllabus, homework assignments and exams
- Evaluated potential course readings, and recommended the appropriate materials
- Topics of instruction included: business models, forms of business, finances and value creation

PUBLICATIONS AND PAPERS
Peer-Reviewed Journal Publications


Publications in Review


Publications in Preparation
Purzer, Ş. **Goldstein, M. H.**, Adams, R. S. Validation of a tool to measure understanding of informed design. To be submitted to the *Journal of Engineering Education*.

**Goldstein, M. H.**, Vieria C., Adams, R. S., Purzer, Ş. Trade-off values as a measurement of design quality. To be submitted to *Design Studies*.

**Goldstein, M. H.**, Purzer, Ş., Adams, R. S. An investigation of the relationship between student design rationale and quality of design solution. To be submitted to the *Journal of Pre-College Engineering Education Research*.

**Goldstein, M. H.**, Purzer, Ş., Adams, R. S. Student conceptions of design and quality of design solution: A comparison of design priorities and design strategy in student designers. To be submitted to the *Journal of Engineering Education*.

**Peer-Reviewed Conference Proceedings (in reverse-chronological order; *presenting author)**


Book Chapters


WORKSHOPS & INVITED TALKS

NextProf Workshop, invited attendee, University of Michigan, September 27-30, 2016.


PROFESSIONAL WORK EXPERIENCE

Trinity Consultants, Lenexa, Kansas
2009-2013

An environmental engineering consulting firm.

Senior Consultant – Air Quality

- Provided technical and analytical support to clients with regulatory compliance issues including: air dispersion modeling analyses, best available retrofit technology (BART) analyses, regulatory applicability analyses, construction permitting, emission inventories, toxics release inventories (TRIs), Tier II reports and greenhouse gas analyses and reports, as well as implementation of environmental management information Systems (EMIS)
- Performed dispersion modeling studies to assist industrial facilities in assessing the impact of their emissions on ambient air quality
- Managed multiple projects at concurrent times including teams of internal staff, client relationships, budgeting and project deliverables

Hay Group, Kansas City, Missouri
2007-2009

A global management consulting firm.

Associate Consultant – Reward Strategies

- Provided project management and analytic support in a wide variety of industries by working with clients at all levels in an organization, supervising analyst and professional staff activities, and ensuring timely project progress
- Acquired critical interpersonal skills and business acumen through executive interviews, strategy clarity sessions and implementation processes
- Conducted analyses, prepared technical reports, and assisted clients in implementing desired changes
- Performed market pricing activities and prepared compensation conclusions and recommendation on a wide variety of reward consulting projects
- Managed firm technologies with creative adaptations to standard tools such as Excel, and helped troubleshoot and champion new client technology such as Job Evaluation Manager (JEM)

Medela, Inc., Illinois,

Summer 2003

The leading breast pump company globally

First intern of the company

- Conducted research on competitive bottle threads and venting systems to produce a more marketable nipple
- Delivered key research and experimentation for many new products
- Streamlined the production line for more effective time management
- Developed mathematical model for optimal flow
**Professional Memberships/Involvement**

Women in Engineering (WIE), National Society  
2013-

American Society of Engineering Education (ASEE)  
2013-

Engineers without Borders (EWB), Kansas City Chapter, Learning Partnership & Education Liaison  
2010-2012
- Worked within the community and promote and engage students, particularly ages K-12, on the work of EWB and the engineering profession in general
- Coordinated educational forums and guest presentations in order to grow capacity and introduce membership to new ideas and opportunities

Air and Waste Management Association (AWMA),  
2010-
- President Purdue Chapter, 2014-2015  
- Midwest Section Young Professionals Co-Chair, 2010-2013

**Institutional Service & Leadership**

Engineering Education Graduate Student Association (ENEGSA), Health and Wellness Committee co-chair, Purdue University  
2015-2016
- Organized health and wellness activities in response to the College initiative for funding

Engineering Education Graduate Committee Chair, Purdue University  
2014-2016
- Reviewed graduate department policies and served on the graduate admissions committee
- Lead initiative to begin mentoring relationships between incoming graduate students and current graduate students

Reinstituted & Served as President of Purdue Student Chapter of Air and Waste Management Association (PAWMA), Purdue University  
2014-
- Multidisciplinary organization “homed” in Civil Engineering  
- President 2014-2015

Co-founder and Treasurer, General Engineering Graduate Organization (GEGO), University of Illinois

2004-2006
PUBLICATIONS

Peer-Reviewed Journal Publications


Publications in Review

Peer-Reviewed Conference Proceedings (in reverse-chronological order; *presenting author)


Book Chapters