Early Design Decisions in Building Materials for Higher Performing Buildings

by

Rebekah D. Burke

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved April 2018 by the
Graduate Supervisory Committee:

Kristen Parrish, Chair
G. Edward Gibson
Braden Allenby

ARIZONA STATE UNIVERSITY

May 2018

ABSTRACT

High performing and sustainable building certification bodies continue to update their requirements, leading to scope modification of certifications, and an increasing number of viable sources of environmental information for building materials. In conjunction, the Architecture, Engineering, and Construction (AEC) industry is seeing increasing demand for such environmental product information. The industry and certifications are moving from using single attribute environmental information about building materials to lifecycle based information to inform their design decisions.

This dissertation seeks to understand the current practices, and then focus on strategies to effectively utilize newer sources of environmental product information in high performance building design. The first phase of research used a survey of 119 U.S.-based AEC practitioners experienced in certified sustainable building projects to understand how the numerous sources of environmental information are currently used in the building design process. The second phase asked two focus groups of experienced AEC professionals to develop a Message Sequence Chart (MSC) that documents the conceptual design process for a recently designed building. Then, the focus group participants integrated a new sustainability requirement for building materials, Environmental Product Declarations (EPDs), into their project, and documented the adjustments to their specific design process in a second, modified MSC highlighting potential drivers for inclusion of EPDs. Finally, the author examines the broader applicability of these drivers through case studies. Specifically, 19 certified high-performance building (HPB) case studies, for reviewing the impact of three different

potential drivers on the design team's approach to considering environmental product information during conceptual design of a HPB, as well as the projects certification level.

LEED certification has changed the design of buildings, and the new information sources for building materials will inform the way the industry selects building materials. Meanwhile, these information sources will need to expand to include a growing number of products, and potentially more data as the industry's understanding of the impacts of building materials develops. This research expands upon previous research on LEED certification to illustrates that owner engagement and commitment to the HPB process is a critical success factor for the use of environmental product information about building materials.

As my experience at Arizona State University comes to a close, I am filled with gratitude. The universe has sent me the perfect people for the perfect lessons – all of those individuals and situations have ushered me toward my higher good.

(Inspired by the Louise Hay "I Can Do It" calendar)

Years and miles have strengthened a love I only thought existed in poems and mythology. Karl David Raymond, you are the most patient, supportive, and kind person I have ever known. Your love means the world to me, and makes all the challenges worth it, and all the good even better.

I dedicate this experience, and my full recognition of the impacts of my life experience, to the woman who taught how to appreciate all aspects of the process, my mother, Dr. LaDona Knigge. Thank you and I love you.

ACKNOWLEDGMENTS

I would like to acknowledge the countless hours of guidance and mentorship provided by Dr. Kristen Parrish, my committee chair. Your tireless support, enthusiasm, and commitment to my success reminds me how powerful believing in someone can be. You are a true inspiration.

Further I would like to acknowledge the invaluable insight provided by my committee members. Dr. G. Edward Gibson, Jr. inspires me with his excellence in industry and academic partnerships, that I will continue to aspire to in my career. I will forever hear Dr. Braden Allenby's (Brad's) gentle prodding to always look at the bigger picture and the unintended consequences, and to examine what is happening at the boundaries.

Thank you to the Architecture, Engineering, and Construction industry, for your partnership in research, and for the industry experience in my career path that has inspired my passion and commitment to excellence in the profession.

Thank you to all my research partners and co-authors over my three ASU research projects; Kristen Parrish, Mounir El Asmar, G. Edward Gibson, Jr., Amy E. Landis, Melissa M. Bilec, Mohammad El Zomor, Claire L. A. Dancz, Kevin J. Ketchman, Troy A. Hottle, Cliff Davidson, and Treavor Boyer.

I appreciate the encouragement and support of my East coast friends; Mel & Neal, Jenny & Jeremie, Steven & Andrew, Leslie & Adam, Erin & Dan, and Shelley. Thank you for the collegiality of my ASU office and classmates over the last three and a half years.

Thank you to my family; Dr. LaDona Knigge, Mike Burke, Michael and Megan Burkarski, Grandma Alyce Knigge, and Aunt Jodi Sprague. I can't possibly thank my boyfriend, Karl, enough, for his kind and patient love over the years and miles, and his children Brandon and Breanna, and their Bermudian family.

The material within this dissertation is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1311230.

TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER 1 – INTRODUCTION

As of 2015, Architecture, Engineering, and Construction (AEC) firms in the US report that high-performing building (HPB) construction accounts for approximately 33% of their projects (Buckley & Logan, 2016). Building certifications, e.g., Leadership in Energy and Environmental Design (LEED), Green Globes, and The Living Building Challenge, have increased the visibility of the AEC industry's impact on the environment and efforts to curtail these impacts. Similar to the update cycle for building codes, HPB certifications are updated, and continue to push the AEC industry for even higher performance buildings with less environmental impact, throughout their lifecycle, that provide a healthier interior for the occupants. The updates to certification requirements lead to changes in the methods and information used to document the successful design and construction of such buildings.

The demand for construction materials has expanded rapidly, increasing 80% from 1980 to 2008, with economic growth closely tied to this demand (OECD, 2015). Additionally, construction and demolition waste accounts for 534 million tons of debris, twice the amount generated from municipal waste (Office of Land and Emergency Management, 2016). Thus, HPB rating systems address both construction materials and construction waste. To address materials, each HPB rating system requires a number of different environmental product information sources to satisfy the certification requirements for pertinent building materials. Similarly, HPB rating systems offer points for recycling construction materials during demolition and construction activities (Green Building Initiative, 2016b; U.S. Green Building Council, 2013).

The U.S. Green Building Council's (USGBC) LEED rating system certified 3,366 projects in 2016, accounting for the majority of buildings certified as high performing in the US (U.S. Green Building Council, 2017). The initial public version of LEED, released in 2000, included 18 points for eight different credits related to sustainable building materials, which accounted for 26% of the total points available. For the purposes of this research, this includes all of the available credits within the "Materials and Resources" credit category, and the "Low-Emitting Materials" credits within the "Indoor Environmental Quality" credit category. In order to earn these credits, designers were required to produce environmental product information describing recycled content, regional materials, renewable resources, certified wood declarations, and volatile organic compound (VOC) content (Building Design & Construction, 2003).

Despite changes to LEED over time, this same documentation still supports earning LEED credits related to building materials. Credits related to building materials accounted for up to 20% of the total available points in USGBC's LEED 2009 (aka LEED v3) for New Construction, first available in April 2009 (U.S. Green Building Council, 2009). This 20% was maintained in USGBC's newest version of LEED, LEED v4, released in November 2013. The updates in LEED v4 were heavily focused in the credits related to building material selection, and included the addition of several new paths to credit achievement, in addition to the paths that were available in previous versions (U.S. Green Building Council, 2013). For example, LEED v4 introduced Cradle to Cradle (C2C) certification, life cycle assessment (LCA), and Environmental Product Declarations (EPDs) to the building material credit requirements. LEED v4 explicitly references EPDs in a new credit to this version, the "*Building Product Disclosure and*

Optimization-Environmental Product Declaration" credit; EPDs can be used to document compliance with the credit requirements for 1-2 points (out of a total of 100 available points) in all building types available in the New Building Design and Construction version (U.S. Green Building Council, 2013).

The Green Building Initiative's (GBI) Green Globes system certified 207 projects in the US in 2016 (Green Building Initiative, 2017). Points related to building materials account for 12.5% of the total available points in Green Globes for New Construction. This system recognizes EPDs, sustainable wood certificates, and whole building life cycle assessments (LCA) as acceptable submittals for the material certification requirements (Green Building Initiative, 2016a).

An EPD communicates verified, transparent, and comparable information about the lifecycle environmental impacts of a product. Due to the expansion of EPD offerings, as well as their increased discussion in HPB rating systems, this research focuses around EPDs as a canonical example of how a new source of environmental product information can be used to inform decisions in the design process.

Motivation

The motivation for this dissertation research project is derived from the experiences I have had in the 14 years I worked in the AEC industry. USGBC's LEED, in partnership with Building Information Modeling and alternative delivery methods, have significantly changed the way we design, construct, and deliver building projects. In the Spring of 2005, I joined with several AEC professionals in the Hampton Roads region to form a local chapter of the USGBC, and to bring educational sessions about sustainable and high-performance buildings to our region. In the fall of 2005, I attended the

Greenbuild International Conferences in Atlanta, and happened by a small conference room where Edward Mazria was announcing the 2030 Challenge, with the primary goal to achieve dramatic reduction in global fossil fuel consumption and greenhouse gas emissions of the built environment. The urgency of his message, and the hard work that was required sparked a fire. Prior to this, I only knew of a couple of agencies in the Department of Defense that were beginning to use LEED, but I began to see a shift as more and more building owners, users, and tax payers were interested in high performance buildings. I committed myself to the idea; supporting what was required to build buildings that are environmentally conscious, energy efficient, and promote health. This entailed changes in our design processes, the information and tools we use, and the composition of our teams and the education they require, and this research allows me to examine and evaluate these impacts thoroughly.

Research Objectives

The overall goal of this dissertation is to determine the most effective strategies to utilize new environmental product information to design and construction buildings. The research has focused on understanding the current strategies for building material selection, then the design team's perception of how to introduce new information into their design process, and then then examination of different influences on a project. The research questions addressed by this dissertation are:

RQ1: What are the strategies being used to inform design and construction decisions for construction materials in high performance buildings?

RQ2: What actions in the design process can an AEC team take to most effectively utilize emerging environmental information for construction materials, in order, to inform design for higher performing buildings?

RQ3: What project characteristics have an impact on the HPB design team's approach and the project's certification outcome?

The dissertation is organized into three individual journal articles as chapters, with each focusing on one of the research questions. The balance of this dissertation is organized in the following manner: Chapter 2 address RQ1, and describes the initial phase of research that utilized a survey to establish the current state of the practice regarding the use of environmental product information, including EPDs, in the AEC design and construction process. Chapter 3 further refines strategies collected from the survey responses to answer RQ2, and uses message sequence charts and transcription data from two focus groups of AEC practitioners to examine the opportunities for utilizing a systems engineering tool as a task precedence model for modifications to conceptual design processes. Chapter 4 addresses RQ3 using case study data collected from 19 HPB projects to examine the impact of three different project characteristics on the design team's approach to considering environmental product information during design of an HPB as well as the project's certification outcome. The last chapter, Chapter 5, summarizes the findings in relation to the three research questions, and provides suggestions for future work.

CHAPTER 2 – ENVIRONMENTAL PRODUCT DECLARATIONS: USE IN THE ARCHITECTURAL AND ENGINEERING DESIGN PROCESS TO SUPPORT SUSTAINABLE CONSTRUCTION

This chapter was published in the peer reviewed journal The Journal of Construction Engineering and Management and appears exactly as published with the exception of text and figure formatting. The citation for this article is: Burke, R. D., Parrish, K., & El Asmar, M. (2018). Environmental Product Declarations: Use in the Architectural and Engineering Design Process to Support Sustainable Construction, *Journal of Construction Engineering and Management, 144*(5), 0401826. doi:10.1061/(ASCE)CO.1943-7862.0001481

Abstract

High performing and sustainable building certification bodies continue to update their requirements, leading to modifications in the scope of certifications, and increasing the number of viable sources of environmental information for building materials. In conjunction, the Architecture, Engineering, and Construction (AEC) industry is seeing increasing demand for such environmental product information. The authors conducted a survey of 119 U.S.-based AEC practitioners experienced in certified sustainable building projects to understand the sources for environmental information, as well as how this information is used in the building design process. The analysis of survey responses forms the basis of this paper, which provides three contributions to the body of knowledge: (1) identifying the AEC professionals' varying experiences with sustainable building certifications and environmental performance information for building materials,

the results show a correlation between use of the LEED rating systems and the exposure of members of the AEC industry to new environmental information sources, (2) identifying the differing levels of knowledge and utilization of the Environmental Product Declaration (EPD), a new environmental information source, a majority of the survey respondents that had utilized any environmental information sources were familiar with EPDs, and (3) providing insight into EPD utilization and guidance from early adopters for effective future use. These findings can help the AEC industry efficiently implement EPDs into their design and construction processes, and better understand the environmental impacts of building materials used in construction.

Introduction

As of 2015, Architecture, Engineering, and Construction (AEC) firms in the US report that high-performing building construction accounts for approximately 33% of their projects (Buckley & Logan, 2016). Building certifications, e.g., Leadership in Energy and Environmental Design (LEED), Green Globes, and The Living Building Challenge, have increased the visibility of the AEC industry's impact on the environment and efforts to curtail these impacts. Additionally, building certifications seek to improve and promote the health and comfort of the building occupants. Building certifications have already changed the way buildings are designed and constructed (Kibert, 2016). As the certifications are updated, they continue to push the AEC industry for even higher performance buildings with less environmental impact throughout their lifecycle while also providing a healthier interior for the occupants. The updates to certification requirements also lead to changes in the methods and information used to document the successful design and construction of such buildings.

The terms high-performance, green, and sustainable buildings may each have nuanced definitions for many people. For others, these terms may be interchangeable. For this paper, and in the survey that informs this study, the authors use the term high performance building (HPB). The authors define an HPB as a building that has been certified, or one whose design was verified by a third party to meet that third party's specified sustainability requirements.

The growth of the HPB market seems to go hand-in-hand with the growth in the certified building products market. Indeed, both the number of certified projects, and the number of sources of environmental information about building products, have grown significantly since 2006 (Kibert, 2016). Building material manufacturers have responded to the AEC industry's demand for new environmental information about their products. While the information provided for a material is an inherent property or characteristic of the product, the information sources are created and verified by a third party. For example, the manufacturers often adjust their product lines to respond to the demands, e.g., adjusting the raw material sourcing for a more regional material, including more recycled content, or the reduction or removal of volatile organic compounds (and hence the "paint smell") from paints and sealants. Environmental Product Declarations (EPDs) describe the lifecycle impacts of a material in a standardized format to support the HPB market. Newer versions of HPB certification systems explicitly list, or in some cases, require EPDs, encouraging many building materials manufacturers to pursue an EPD for their products.

Each HPB system requires varied environmental information sources to satisfy the certification requirements for pertinent building materials. Numerous sustainable building certification systems are in use in the global AEC industry, this paper only discusses the two most commonly implemented by survey respondents within this study: LEED and Green Globes.

The US Green Building Council's (USGBC) LEED rating system certified 3,366 projects in 2016, accounting for the majority of buildings certified as high performing in the US (U.S. Green Building Council, 2017). Credits related to building materials account for 20% of the total available points in USGBC's LEED 2009 (aka LEED v3) for New Construction, which was first available in April 2009 (U.S. Green Building Council, 2009). This 20% was maintained in USGBC's newest version of LEED, LEED v4, released in November 2013. LEED v4 explicitly references EPDs in a new credit to this version, the "*Building Product Disclosure and Optimization-Environmental Product Declaration*" credit; EPDs can be used to document compliance with the credit requirements for 1-2 points (out of a total of 100 available points) in all building types available in the New Building Design and Construction version (U.S. Green Building Council, 2013).

In comparison, the Green Building Initiative's (GBI) Green Globes system certified 207 projects in the US in 2016 (Green Building Initiative, 2017). Points related to building materials account for 12.5% of the total available points in Green Globes for New Construction. This system recognizes EPDs, sustainable wood certificates, and whole building life cycle assessments (LCA) as acceptable submittals for the material certification requirements (Green Building Initiative, 2016a).

Research Objectives

The AEC industry has seen changes in the building material information required during design and construction alongside the growing demand for HPBs. LEED is the most widely adopted rating system, which saw significant changes in LEED v4 for the way materials contribute to certification with the introduction of EPDs as a path for credit compliance. With EPDs being a new source of information widely used in the AEC industry, it is not clear how the industry will utilize them in their design, and the influence they will have on the overall environmental impact of a building.

This paper examines three research objectives. First, the paper explores the current state of practice for some of the most common environmental information sources by examining firm policies for incorporating the information into design and construction. The paper additionally examines the different AEC disciplines' experience with the sources and the influence of different rating systems on their use. Second, the authors explore the differences in the various AEC disciplines' current knowledge and utilization of EPDs. The third objective of this study is to provide insights from early adopters on the value of EPDs in the design process and offer guidance for future EPD use.

Literature Review

Single attribute environmental information provides data about one aspect of a building material, which comes from a variety of sources, such as sustainable wood certificates, recycled content (RC), renewable resource content (RRC), regional material content (RegC), and volatile organic compound (VOC) content. Single attribute environmental information is typically verified by a third-party organization. Certified wood certificates (CWD) document that the wood used in a building material has been grown in a forest that is sustainably managed and harvested. Recycled content is the percentage of post- and pre-consumer recycled content in a building material. Renewable resource content is a quantification of the raw material that comes from a resource that will regenerate within 10 years. Building materials that are extracted, manufactured, and purchased within a specific radius of the construction site (e.g., 100 miles in LEED v4) are considered regional materials.

Research regarding the utilization of single attribute environmental information sources focuses on a specific material, e.g., wood, concrete, steel, or comparisons of them (Kam-Biron & Podesto, 2011). With the exception of Chick and Micklethwaite (2004) research on recycled content for building materials in the UK, there has been little research focusing on the AEC industry's overall utilization of these environmental information sources. Research shows there are differences in the environmental impact of several material choices, such as a difference between a steel and concrete superstructure, and the studies commonly rely on the material information of a single project for validation. The existing literature does not explore how the industry views, values, and uses various sources of environmental information to inform design (Gelowitz & McArthur, 2016).

Cradle to Cradle (C2C) certificates, life cycle assessments (LCA), and EPDs are environmental information sources that address multiple characteristics of a building material or an assembly of several materials. Products can earn C2C certificates based on five quality categories: material health, material utilization, renewable energy and carbon management, water stewardship, and social fairness, which are assessed by an independent organization (Cradle to Cradle Products Innovation Institute, 2017b). In comparison, LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, and are created according to guidelines, with ISO 14040-14044 being the most prominent in the US (Baumann & Tillman, 2004). Finally, EPDs are LCA results intended to be communicated in market situations for comparability. Therefore, EPDs need to be more standardized than LCAs and the results must be independently verified. EPDs are created in accordance with ISO 14025 and EN 15804 using LCAs developed according to ISO standards 14040 and 14044.

Several authors explore the challenges and opportunities for LCA incorporation into the design and construction process, focusing on LCA use in buildings (Anand & Amor, 2017; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Lamé, Leroy, & Yannou, 2017; Olinzock et al., 2015; Saunders, 2013). These studies reveal LCA is underutilized in projects, which is frequently attributable to lack of demand from clients. However, designers see LCA as an important tool to inform decision making. Additional challenges to the use of LCA to inform design are the lack of tools, or effective tools to assist in their use. Zhong, Ling, and Wu (2017) and Bakhoum and Brown (2012) have created models or scoring methods to help select a structural system partially based upon information commonly contained in an LCA, such as global warming potential and ozone depletion, as well as embodied energy. Lamé et al. (2017) noted the prevalence of models and other design tools created by academia have not resulted in increased use of LCA information for AEC industry design decisions, as those do not directly address the designers' need and other factors specific to the AEC industry. While authors discuss the potential value of LCA and other multi-attribute environmental information sources for the AEC industry, literature documenting the use of such information in the industry is sparse.

EPDs have recently been adopted by HPB certification systems, presumably to utilize the information from LCAs in a manner most appropriate for the AEC industry. At the time of publication, EPDs are registered for approximately 700 products in 13 categories with the International EPD® System, ranging from food to fuel to services. The "Construction Products" category comprises 383 EPDs, including EPDs for structural steel, light fittings, plumbing fixtures, various wall, floor and ceiling finishes, and many other building materials (EPD International AB, 2017).

This paper fills three important gaps in the literature. First, the authors explore how environmental product information is viewed, valued, and used in the AEC industry. Second, the paper examines how the AEC industry views, values, and uses EPDs – a new source of environmental information in today's industry. Lastly, insights are provided based on early adopters' experiences with EPDs.

Research Methodology

This section describes the development of the survey administered for this study, as well as the quantitative and qualitative data analysis methods used to examine the responses. The quantitative survey responses are binary or ordinal data using a Likert scale, and were analyzed with the Mann-Whitney U-Value statistical test. The qualitative survey responses are based on open-ended questions and were analyzed with NVivo.

Survey Development

The authors developed a survey to gain insights into the AEC industry's utilization of environmental information sources to inform material decisions. The survey was developed based on components of several previous industry surveys about building material environmental information sources and use (Hofstetter & Mettier, 2003; Olinzock et al., 2015; Rodriguez-Nikl, Kelley, Xiao, Hammer, & Tilt, 2015; Said & Berger, 2014). Fourteen participants grouped in two focus groups of seven participants each, from two full-service architecture and engineering firms, tested and provided feedback on the survey, and then the authors distributed the survey online through three avenues. Table 1 shows the survey distribution avenues and the potential reach of each. A total of 119 responses were received for an estimated response rate of 13.5%.

Table 1. Online survey distribution avenues and their potential reach

Avenue	Potential reach
Business cards distributed at Greenbuild 2016	250 contacts
Social media distribution (LinkedIn, Facebook)	550 contacts
USGBC Chapter newsletters (Arizona, Colorado, Hampton Roads, Greater Virginia)	80 contacts*

* based upon an average 10.5% email open rate, and 1.7% average link click for opened email

The survey consisted of 5 sections: (1) individual demographics, (2) HPB experience, (3) sources of building material environmental information accessed, (4) experience with EPDs, and (5) company demographics. The online survey questions were conditional, adjusting the flow and number of questions a respondent would be presented based upon previous responses. Figure 1 illustrates the survey flow and number of responses for each section.

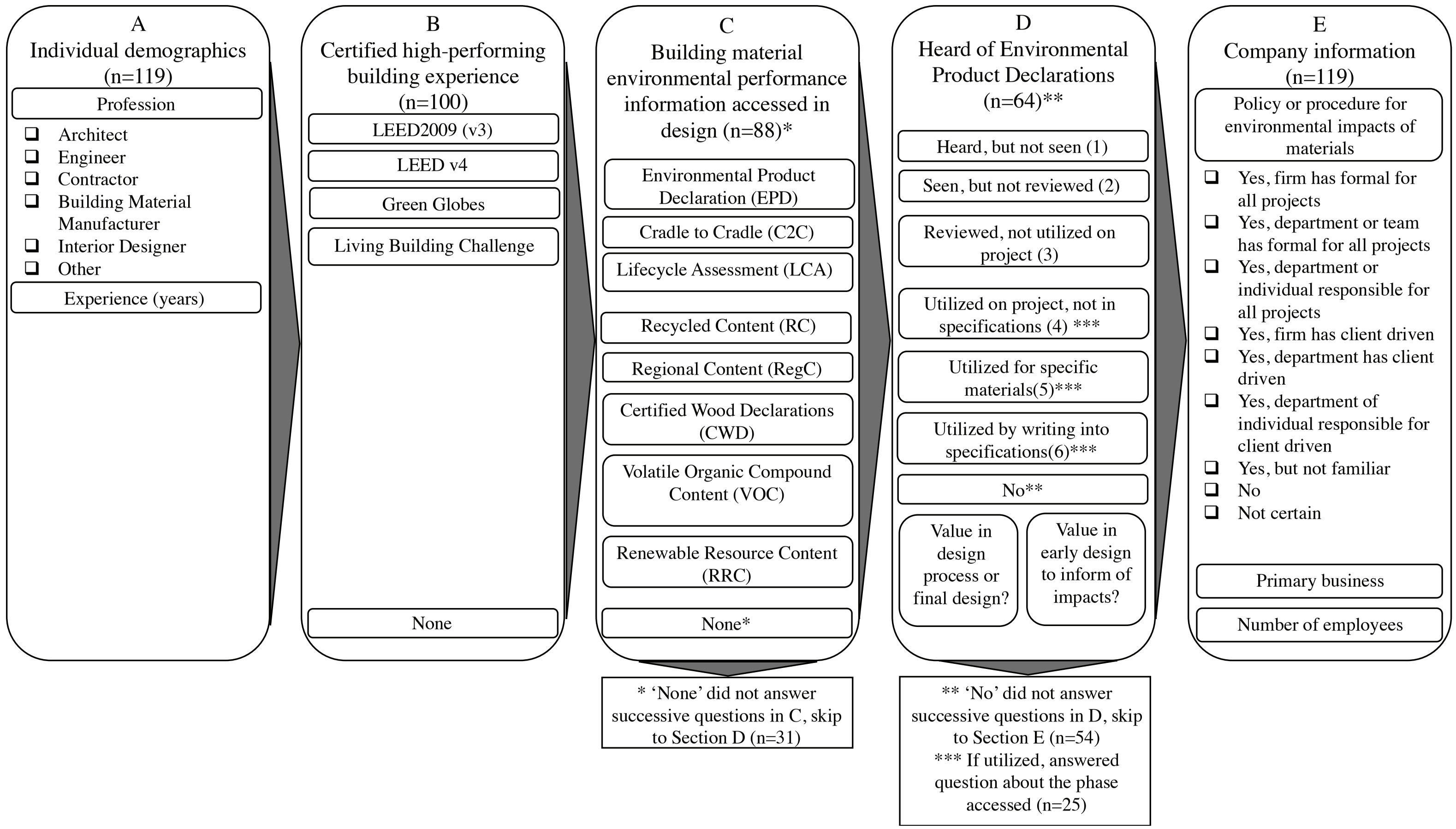


Figure 1. Online survey sections and flow

Data Collection

Once the survey was developed, it was administered online via Qualtrics and data was collected. Table 2 displays the average experience and number of respondents from each profession that responded to the survey. The 119 respondents have an average experience of 18.5 years. Moreover, as shown in Figure 2, the majority of respondents were from firms with greater than 1500 employees (27%), followed by 201-500 employees (20%). In Figure 3 we see the majority of respondents were from full service architecture and engineering firms (30%), followed by “other” (23%). Respondents that selected “other” as their profession, or “other” for their primary business type, reported they were owner representatives, LEED/green building/energy consultants, governmental entities, or researchers.

Table 2. Survey respondent profile

Profession	Average Experience (yr)
Architect (n=47)	20.9
Building Material Manufacturer (n=4)	15.8
Contractor (n=23)	18.3
Engineer (n=22)	19.9
Interior Designer (n=7)	9.6
Other (n=16)	14.8
Total Survey Respondents (n=119)	18.5

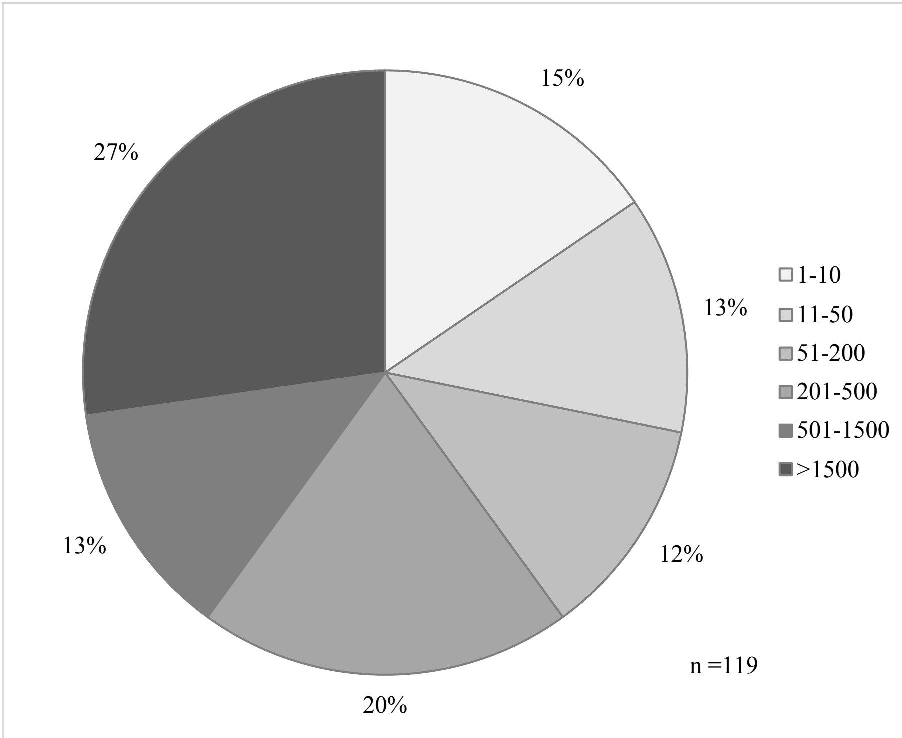


Figure 2. Survey respondent's firm size (Employees)

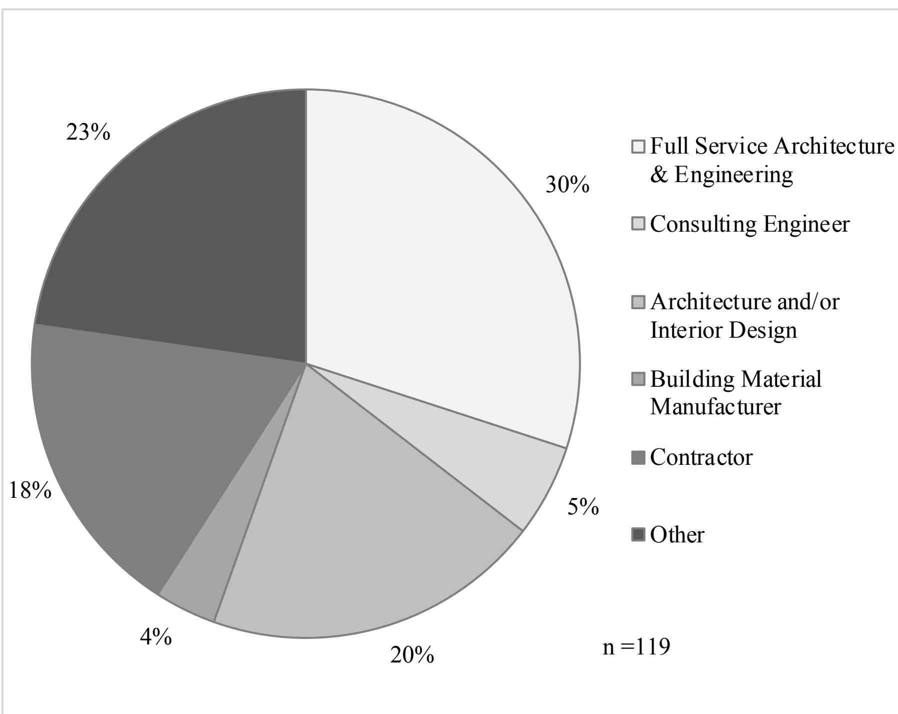


Figure 3. Survey respondent's firm's primary business

Respondents that reported completion of an HPB or current work on an HPB project indicate that they have completed 12 HPB projects on average (Table 3). “Other” respondents reported a much higher average number; which is likely attributable to the consultants that classified themselves as “Other” who specialize in HPBs that may engage with more sustainable building projects at a time than other AEC professionals. An outlier analysis, which counts beyond three standard deviations from the median, removed eight respondents who reported HPB project experience numbering above 100.

Table 3. The average number of HPBs a respondent has completed, by profession

Profession	Average Number of Certified Buildings
Architect (n=38)	14
Building Material Manufacturer (n=4)	8
Contractor (n=20)	5
Engineer (n=22)	7
Interior Designer (n=4)	7
Other (n=12)	33
Total Respondents with certified building experience (n=100)	12

Data Analysis

The authors performed univariate statistical analyses of the survey data through two complementary lenses: (1) the responses of specific disciplines compared to the rest of the sample, and (2) the responses of participants with specific HPB experience compared to those without HPB experience. For the quantitative data, the Mann-Whitney

U-test was used; it is a non-parametric statistical test applicable when the data are not normally distributed, the two sample groups are unequal in size, and one may be significantly smaller than the other (David J. Sheskin, 2007). The data analyzed meet these conditions, and this test has been used regularly when analyzing AEC industry quantitative data in previous studies (Asmar, Hanna, & Loh, 2013; Minchin, Li, Issa, & Vargas, 2013). The test compares the medians of two samples, with the null hypothesis being that the medians are the same. The analysis was completed using the SPSS statistical software.

Moreover, the qualitative survey results were analyzed using a qualitative software coding program, NVivo. NVivo has been used regularly to code and analyze AEC industry qualitative data in previous studies (Javernick-Will, 2012; Rodriguez-Nikl et al., 2015). The two open-ended questions were coded into themes ("nodes" within NVivo). The software allows the authors to manage the data and create queries within the qualitative data with reference to the multiple-choice questions, creating codes to report the results. This qualitative analysis is used to amplify and expand upon the quantitative analysis presented in this paper.

Results and Discussion

Next, the authors present the survey results and discussion in three sections corresponding to the research objectives.

Overall Environmental Product Information Use

The survey asked respondents about their firm's policy for evaluating environmental product information for use in the design and construction process. Twenty-four percent (24%) of respondents reported they had some form of policy or procedure, 43% reported they did not have one, and 11% were not certain if their firm had a policy or not. The remaining 22% of respondents did not answer the question and are removed from the reported percentages in the rest of this section. A firm with 11-50 employees was most likely to have a policy for evaluating environmental product information, with 50% of respondents from that size firm reporting they have a policy to review environmental product information for use in design and construction. Firms with 501-1500 employees were the least likely to have a policy with 83% reporting they did not have a procedure or policy to review environmental information, which was not a result that could be explained from previous research. However, a review of the respondents from firms with 501-1500 employees revealed a large proportion of the firms were contractors, which were the least likely to have a policy, and the least likely to know if they had a policy, with 7% reporting they have a policy, and 43% not sure if they have a policy. Consulting engineering firms (50%) and architecture and interior design firms (39%) were the most likely to have a policy or procedure to evaluate environmental information for use in the design and construction process.

The survey questioned respondents about their overall environmental product information use as well as the specific information sources used. The authors examined the responses for trends, correlations, and statistical significance by discipline and then in relation to the respondents' experience with specific HPB rating systems.

Analysis by Discipline (Architect, Engineer, Contractor)

Respondents indicated whether or not they had ever accessed environmental information about building materials. Seventy-four percent (74%) of all survey respondents had utilized environmental information for building materials during the design process. Table 4 shows the Mann-Whitney U-value statistic for each of the three major AEC disciplines compared to the balance of survey respondents. Overall, utilization is not statistically different between any of the disciplines compared to the respondents from outside that discipline (i.e., no difference between architects and non-architects).

This finding illustrates that all disciplines of the AEC community leverage environmental information about building materials. As indicated by the relatively high p-values (none are below the 0.05 threshold which indicates statistical significance at a 95% confidence level), all disciplines report using such information about building materials on a project. However, the specific information sources may not be the same across disciplines. Figure 4 shows the information sources each discipline has accessed.

Moreover, Table 5 presents results of the statistical analysis of this data and is discussed in detail in the following paragraphs.

Architects access more sources of environmental information compared to other disciplines, with the information sources EPD and Cradle 2 Cradle (C2C) being exceptions. This may be attributed to an architect's typical role in selecting building materials and writing product specifications, only relying on the input of other disciplines for guidance on distinct material issues (Holloway & Parrish, 2015). Eighty-one percent (81%) of architects have accessed environmental information from at least one of the sources listed; with more than 90% of those having accessed recycled content, regional content, and VOC content. In fact, architects' access of each of these sources is statistically significant ($p < 0.05$) when compared with other disciplines (Table 5).

Table 4. Comparison of the different disciplines' use of environmental information about building materials

Architect (n=47) Other respondents (n=72)			Contractor (n=23) Other respondents (n=96)			Engineer (n=22) Other respondents (n=97)		
Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)	Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)	Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)
1499	-1.380	0.168	1104.5	0.004	0.996	1261.5	1.751	0.080

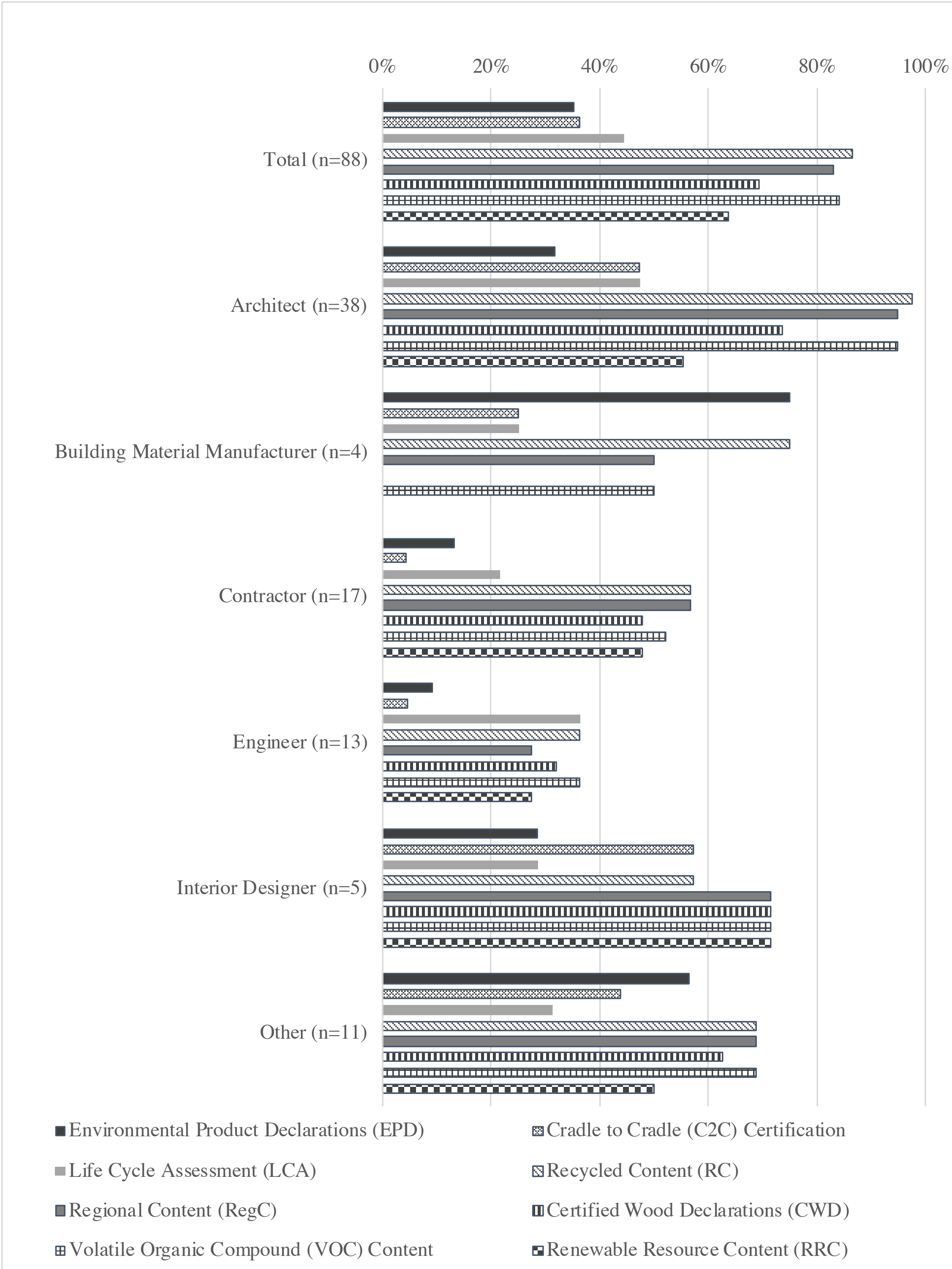


Figure 4. Building material environmental information sources accessed by each discipline

Table 5. Comparison of each discipline's access of several forms of building material environmental information during design

** Indicates statistical significance*

	Architect (n=38) Other disciplines (n=50)			Contractor (n=17) Other disciplines (n=71)			Engineer (n=13) Other disciplines (n=75)		
	Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)	Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)	Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)
EPD	1011	0.621	0.535	735	1.680	0.093	601	1.613	0.107
C2C	766	-1.860	0.063	831.5	2.892	0.004*	651.5	2.315	0.021*
LCA	899	-0.499	0.618	715	1.370	0.171	389	-1.346	0.178
RC	766	-2.608	0.009*	677.5	1.316	0.188	629.5	2.809	0.005*
RegC	753	-2.548	0.011*	652	0.787	0.431	698	3.800	0.000*
CWD	877	-0.770	0.441	638	0.456	0.648	576	1.303	0.193
VOC	772	-2.367	0.018*	704.5	1.685	0.092	616.5	2.394	0.017*
RRC	870	-0.809	0.419	595.5	-0.101	0.919	578.5	1.411	0.158

Engineers have accessed C2C certifications, recycled content, regional content, and VOC content significantly less than the rest of the survey population ($p < 0.05$) (Table 5). This may also may be attributed to the role of an engineer, who often does not necessarily select building materials, but provides guidance to the architects when they select materials and write specifications. Fifty-nine percent (59%) of engineers have accessed environmental information from at least one of the sources listed; with less than 40% of those having accessed any one environmental information source (Figure 4). Seventy-four percent (74%) of contractors have accessed environmental information from at least one of the sources listed. Of those that have accessed any, they have accessed C2C certifications (4%) and LCA (22%) less than the rest of the survey population (Figure 4), with C2C certifications being statistically significant (Table 5). Research examining a contractor's role in the HPB design and construction process commonly contains a recommendation to include the contractor early to help inform the process (e.g., (Schaufelberger & Cloud, 2009)). This finding, coupled with result above, showing contractors are the least likely to have a policy to consider environmental information source, confirms contractors are not commonly accessing information that could be used to inform the environmental aspects of material selection in design and construction.

Interior designers access C2C certifications more than any other discipline, with 57% of interior designers reporting they have accessed C2C certifications (Figure 4). This fact may be attributed to the large portion of the C2C certificates available for finishes and furniture, which are primarily specified by interior designers. Thirty-seven percent (181) of the 487 C2C certifications are “Building Supply & Materials”, with 12% (57) related to finishes and flooring. Additionally, 34% (167) of the available C2C certificates are “Interior Finishes or Furniture” (Cradle to Cradle Products Innovation Institute, 2017a).

In comparison, when it comes to EPDs, building material manufacturers and “other” respondents accessed EPDs more than any other discipline, with 75% of building material manufacturers, and 56% of “others”, respectively, accessing EPDs (Figure 4). This seems reasonable given building material manufacturers commonly are required to provide data about their specific materials for each of the different environmental information sources listed. Similarly, “other” respondents are typically consultants that specialize in HPBs, so it stands to reason that they may have more need to access the environmental information sources than other respondents.

Analysis by Certification Experience (LEED 2009, LEED v4, Green Globes)

More than 60% of survey respondents that accessed environmental information had employed each of the sources referenced by LEED 2009 and earlier versions of LEED. Specifically, respondents indicate they had accessed recycled content (RC) (86%), volatile organic compound content (VOC) (84%), regional content (RegC) (83%), certified wood documents (CWD) (69%), and renewable resource content (RRC) (64%), all of which are explicitly referenced in LEED 2009, as well as LEED v4 and earlier versions of LEED. With statistical significance ($p<0.05$), the respondents' experience on a LEED 2009 project, either currently in progress or completed, was a determining factor in them having accessed EPD, LCA, RC, and RRC (Table 6). There is a strong correlation with respondents that are familiar with LEED 2009 projects and their

Table 6. Respondents who have, or have not, worked on or complete HPBs for various sources of building material information

* indicates statistical significance

	Have worked on or are currently working on a LEED2009 (v3) Project (n=52) Not (n=35)			Have worked on or are currently working on a LEED v4 Project (n=26) Not (n=61)			Have worked on or are currently working on a Green Globes Project (n=8) Not (n=79)		
	Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)	Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)	Mann-Whitney *U*	*z*	*p*-value (Asymptotic Significance, 2-sided test)
EPD	1140.5	3.077	0.002*	1118.5	4.101	0.000*	345.5	1.232	0.218
C2C	1042	1.789	0.074	942.5	1.660	0.097	259.5	-0.444	0.657
LCA	1088	2.199	0.028*	1069	2.971	0.003*	323	0.708	0.479
RC	1020.5	2.16	0.031*	762	-0.499	0.618	281.5	-0.052	0.959
RegC	928	0.723	0.470	801	0.117	0.907	248	-0.84	0.401
CWD	1031	1.729	0.084	883	1.041	0.298	293.5	0.191	0.848
VOC	944.5	0.972	0.331	788	-0.075	0.940	332.5	1.193	0.233
RRC	1114	2.426	0.015*	774	-0.211	0.833	267	-0.303	0.762

utilization of environmental information required to document credits within the LEED 2009 rating system, which explicitly references recycled content and renewable resource content but does not reference EPD and LCA. Interestingly, the correlation with LEED 2009 project experience extends to other environmental information sources, suggesting survey respondents with LEED project experience are generally more familiar with existing and emerging environmental information sources for building materials

In addition, the respondents with experience on a LEED v4 project, either currently in progress or completed, was a determining factor in having accessed EPD or LCA for environmental information (95% confidence interval). These results illustrate a correlation between the LEED rating systems and the exposure of members of the AEC industry to new environmental information sources, and may be a driving factor for industry becoming familiar with new information sources. Note the authors also analyzed the data to determine whether or not experience on a Green Globes project correlated to AEC industry exposure to new environmental information sources. The respondents with experience on a Green Globes project, either currently in progress, or completed, did not show a statistically different experience in accessing any of the environmental information sources. The sample size of respondents that have the experience is quite low, but representative of the industry, as Green Globes certified projects represented 6% of LEED certified projects in 2016.

The Current State of EPD Use

The survey asked respondents about their familiarity with EPDs, as well as how they had used the EPDs on projects. The responses regarding familiarity were assigned ranks on a Likert scale (1-6) to facilitate quantitative analysis. Figure 5 shows the text

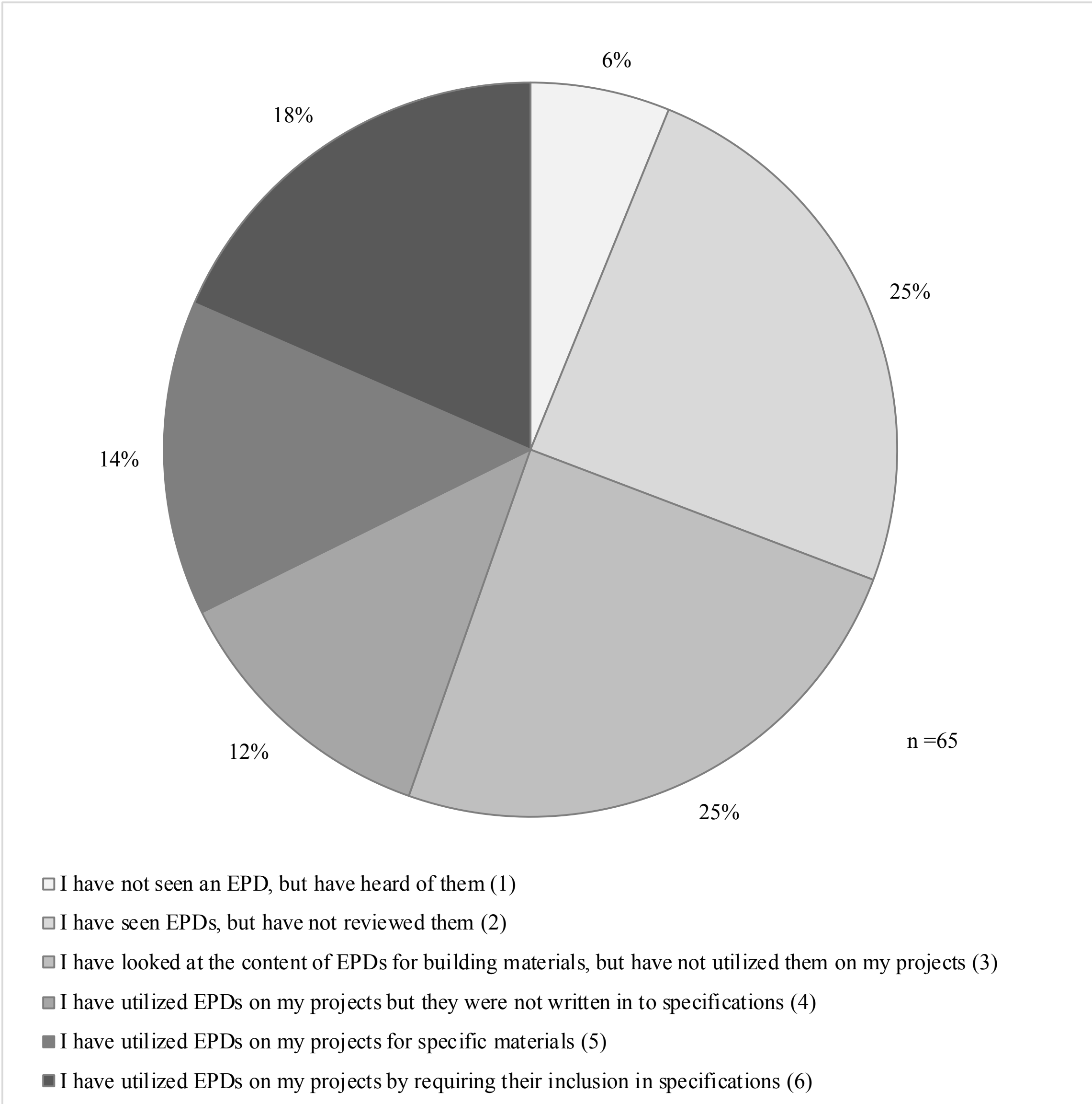


Figure 5. Respondent's familiarity with and use of EPDs. The number in parentheses for each response corresponds to the Likert scale number used in statistical analysis

survey answers with the assigned Likert value. The authors examined the responses for trends and statistical significance in relation to the respondents' experience with specific HPB rating systems.

Of the survey respondents that had utilized any environmental information sources, 56% of them were familiar with EPDs. Of those that were familiar (had at least heard of them), 61% had accessed them for a project (indicated by selecting 4, 5, or 6 on the Likert scale provided), and 30% had included them their specifications, either as performance based-specification (6 on the Likert scale), or by selecting a specific material that had an EPD (5 on the Likert scale) (Figure 5). Respondents that are currently working on or have completed a LEED v4 project or a LEED 2009 project are more familiar with EPDs, with LEED v4 being statistically significant ($p = 0.034$) (Figure 6). The USGBC strives to continuously update the LEED rating system to reduce the environmental impacts of buildings while improving the internal conditions in said buildings. Results of this study indicate the AEC industry is responding to these improvements; the AEC industry is currently using EPDs to inform design and construction decisions. These results show LEED v4 updates, which explicitly include EPDs as credits for building materials, have acted as a catalyst for the AEC industry to learn about and use EPD.

Insight from EPD Early Adopters

The survey directed respondents who indicated they had utilized EPDs in their design (Likert scale responses 4-6, Figure 5) to further questions, as outlined in Figure 1 (Section D). The respondents selected the phase in the design when they first reviewed EPDs, if they saw value in the EPDs for the design process and/or for the final design product, and if they saw value in reviewing EPDs early in the design process to inform

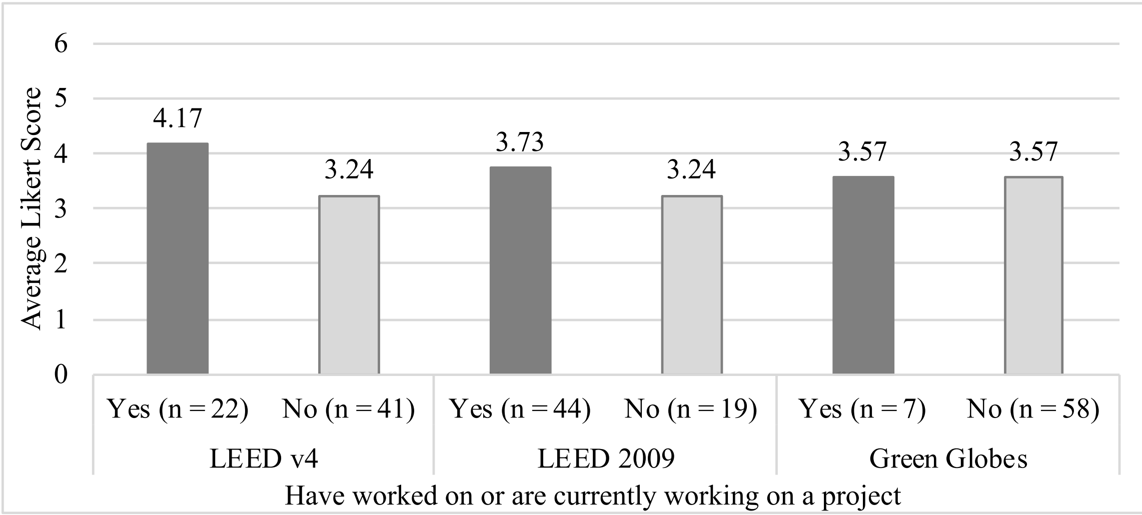


Figure 6. A comparison of the Likert score of respondents who have, or have not, worked on or completed an HPB in terms of their familiarity with and use of EPDs on projects

the design. Additionally, they were asked open-ended questions about the value or valuable information brought to the design process or the final building design, and to provide an explanation why, or why not reviewing an EPD early in the design process provides value.

Value in early use to inform material selection

Fifty-three percent (53%) of all respondents that had used an EPD in their design process had first reviewed them in the pre-design (0-10%) or preliminary design (10-35%) phase (Figure 7). These respondents provide insight into their perceived value of reviewing an EPD early with comments clustering around informed decisions allowing for a better design (20 coded responses), and the early EPD review helps determine the environmental impact or sustainability of the building (16 coded responses). One respondent linked the review of EPDs early in the design process to “lean and value-driven design”. Another respondent who had utilized EPDs in the preliminary design

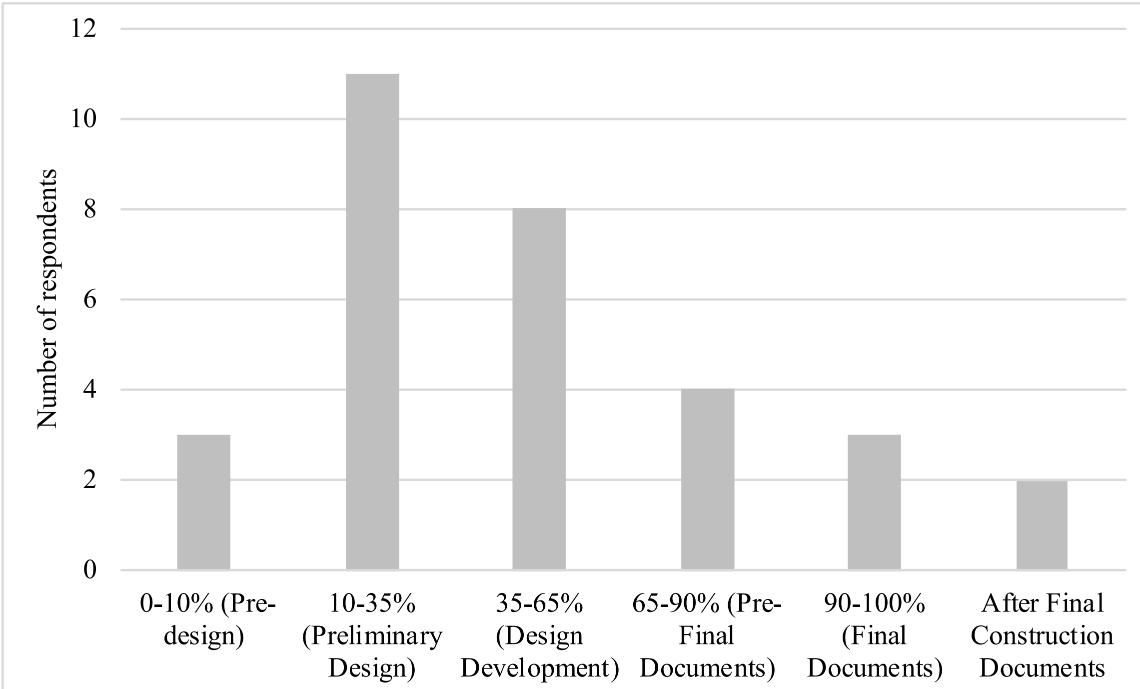


Figure 7. Breakdown of the design phase when the building material EPDs were first reviewed, for all respondents who have used an EPD in their design process

phase (10-35% completion), and thought reviewing them early definitely added value to design process, discussed the values and risks of EPDs: “the *value* is in raised awareness amongst those making decisions…the *risk* is increased liability if a material ends up having an unanticipated adverse impact that the designer should have been able to predict based on seeing this document”.

No survey respondents familiar with EPDs think that EPDs “probably” do not or “definitely” do not provide value in informing the environmental implications of a material selection early in the design process (Figure 8). The higher the level of EPD utilization from a respondent, the more likely that respondent is to believe an EPD "definitely" adds value early in the design process, i.e. 25% of respondents that have only heard of EPD (1 on the Likert scale) think they definitely add value, while 70% of resondents that have written EPDs into their specifications (5 or 6 on the Likert scale) think they "definitely" add value. A respondent who had accessed EPDs for specific materials for a project in the pre-final documents (65-90% design completion) and believed EPDs definitely added value informing the early design commented "In previous projects that used EPDs, I have generally seen them used much later…which is not as useful…to properly use and account for them."

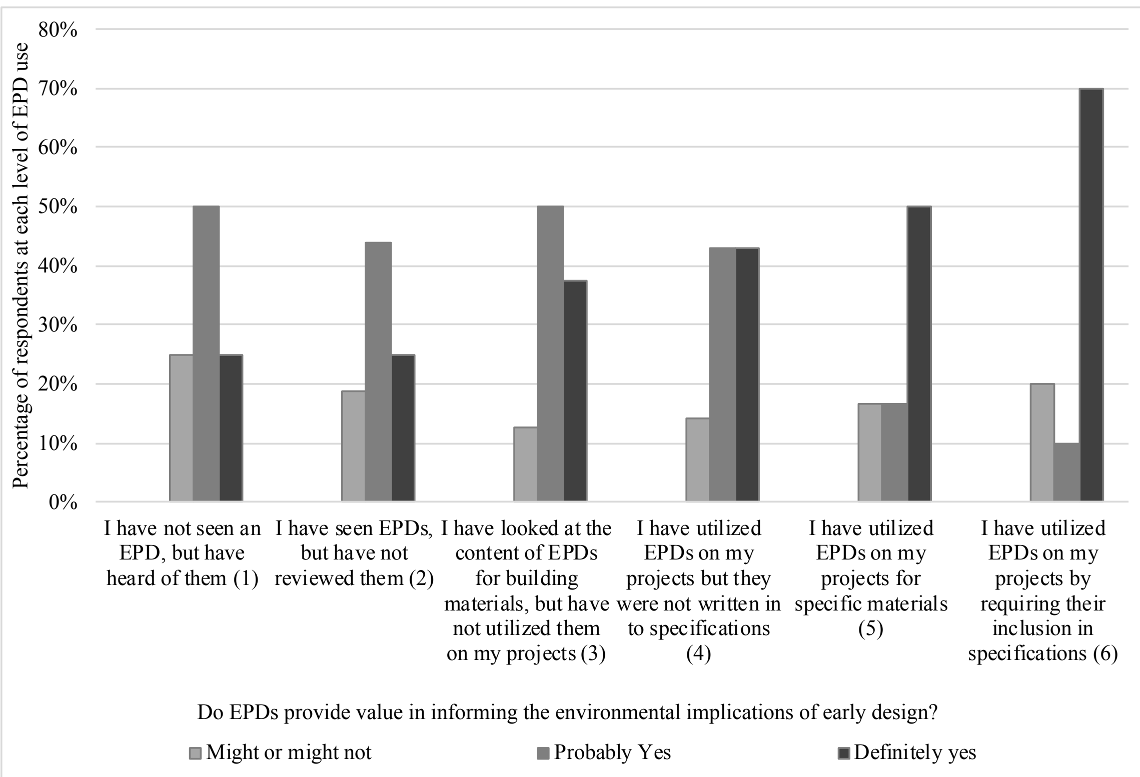


Figure 8. The respondent's use, in relation to their perceived value in reviewing EPDs early in the design process, to inform the design regarding environmental implications of materials

The percentage of respondents that report EPDs "may or may not" provide value in informing the environmental implications of early design is consistent through the levels of EPD use (13-25%). The respondents that think EPDs may or may not provide value early in the design process seem skeptical that EPDs need to be reviewed as early as referred to in the survey (4 coded responses) and identify the owner requirements as critical to the EPDs importance early (2 coded responses). Respondents commented, "Specific materials often aren't selected until much later after…programming is complete" and "although products can inform the design, I feel they are not critical to set the design direction". Neither of these respondents reported the design phase when they had reviewed EPDs for use.

Value of EPD to final design and to the design process

Eighty-seven percent (87%) of respondents familiar with EPDs believe they bring valuable information or value to the building design process, and 36% believe they bring value to the final building. Six percent (6%) do not believe EPDs bring any value to the design process or the final building design, and based upon the comments is because they are too much information.

Based upon the respondents' comments, the valuable information or value to the building design focuses around the themes of easier to analyze and compare sustainable benefits of products through the consistency and transparency of third party verification (5 coded responses), and education of the design team and owner (7 coded responses). A respondent who had utilized EPDs in the design development phase (35-65%) by writing them into their specifications commented, "EPDs save me a lot of valuable time. They help cut through the noise in the market. EPDs help me to expedite my own design process while remaining confident that the materials will satisfy the needs and goals of the project as a whole”. A respondent that looked at EPDs in preliminary design (10-35%) but has not utilized them on a project commented, “[EPDs]…help to define alignment between product / team goals / product selection [and]…educate team, owner, manufacturer”.

The respondents that believed EPDs bring value to the final building design all focused on the environmental impact of design decisions (23 coded responses), such as “critical life cycle information” and “standardized information on the embodied environmental impact”. Several other respondents also commented on being able to provide the owner or client with their desired sustainable building (5 coded responses).

Conclusions

The survey helps conclude in today’s AEC industry, only a small portion of employees, 28% of the total question respondents, report that their firm has a formal or informal policy for evaluating environmental information sources for use of building materials in their design and construction process. Further analysis shows that consulting engineering and architecture and/or engineering firms, as well as smaller firms, are the most likely to have such a policy. However, across firm size and type, the majority of AEC disciplines typically access at least one of the various environmental product information sources available, and most often begin to access them because of their engagement on HPBs seeking LEED certification. Findings further indicate architects as most likely to utilize nearly all of the sources of environmental information queried, with other disciplines providing support as required, consistent with previous research about other components of the design process. Conversely, contractors are the least likely to have a policy regarding the use of environmental product information sources, and are also the least likely to have accessed EPDs.

USGBC's adoption of EPDs in LEED v4 appears to be the catalyst for the AEC industry to use EPDs, with mainly positive results and feedback. EPD users believe there is value in their use and in their incorporation into the design process early to inform the design, as well as helping the owner in their desire for an HPB. Users also acknowledge EPDs are a first step in the right direction, as they facilitate comparison of environmental impacts of building products. However, to truly move the industry standard to HPBs, survey respondents agree that the AEC industry needs EPDs for more products than currently available.

The EPD standardized format is seen as critical to an industry full of diverse environmental information sources, in order to help the AEC industry make practical and informed decisions for the delivery of successful HPBs. Early adopters tend to believe EPDs must be integrated into the design process early. They should be also used as a tool to help inform the owner and design team members about the environmental impact of the building materials selected.

The main limitation of the study is that the results are based on a sample of 880 U.S.-based AEC practitioners. Since this is a relatively small convenient sample, the numbers presented herein should not be assumed to be representative of the whole AEC industry. However, 119 respondents provide a rich and diverse set of experiences to help quantify and understand, for the first time, the use of environmental product information, and specifically EPDs, in engineering design to support of sustainable construction.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data sharing policy can be found here: http://ascelibrary.org/doi/10.1061/%28ASCE%29CO.1943-7862.0001263.

Acknowledgements

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1311230. The authors would also like to acknowledge the time and assistance of numerous industry contacts. The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of data presented herein, and does not necessarily reflect the views of the NSF or survey respondents.

References

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renewable and Sustainable Energy Reviews, 67*, 408-416. doi:10.1016/j.rser.2016.09.058

Asmar, M. E., Hanna, A. S., & Loh, W.-Y. (2013). Quantifying Performance for the Integrated Project Delivery System as Compared to Established Delivery Systems. *Journal of Construction Engineering and Management, 139*(11). doi:doi:10.1061/(ASCE)CO.1943-7862.0000744

Bakhoum, E. S., & Brown, D. C. (2012). Developed Sustainable Scoring System for Structural Materials Evaluation. *Journal of Construction Engineering and Management, 138*(1), 110-119. doi:doi:10.1061/(ASCE)CO.1943-7862.0000412

Baumann, H., & Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA: An orientation in life cycle assessment methodology and application*. Poland: Studentlitteratur.

Buckley, B., & Logan, K. (2016). World green building trends 2016: developing markets accelerate global green growth. *Bedford (MA): Dodge Data & Analytics*.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews, 29*, 394-416. doi:http://dx.doi.org/10.1016/j.rser.2013.08.037

Chick, A., & Micklethwaite, P. (2004). Specifying recycled: understanding UK architects' and designers' practices and experience. *Design Studies, 25*(3), 251-273. doi:http://dx.doi.org/10.1016/j.destud.2003.10.009

Cradle to Cradle Products Innovation Institute. (2017a). Cradle to Cradle Certified Products Registry. Retrieved from http://www.c2ccertified.org/products/registry

Cradle to Cradle Products Innovation Institute. (2017b). Get Cradle to Cradle Certified. Retrieved from http://www.c2ccertified.org/get-certified/product-certification

EPD International AB. (2017). EPD, The Green Yardstick. Retrieved from http://www.environdec.com/

Gelowitz, M. D. C., & McArthur, J. J. (2016). *Investigating the effect of environmental product declaration adoption in LEED on the construction industry: A case study*. Paper presented at the International Conference on Sustainable Design, Engineering and Construction, Tempe, AZ.

Green Building Initiative. (2016). Green Globes for New Construction, Technical Reference Manual, Version 1.45 *Materials and Resources* (pp. 138-206).

Green Building Initiative. (2017). Certified Building Directory. Retrieved from https://www.thegbi.org/project-portfolio/certified-building-directory/

Hofstetter, P., & Mettier, T. M. (2003). What Users Want and May Need: Insights from a Survey of Users of a Life-Cycle Tool. *Journal of Industrial Ecology, 7*(2), 79-101. doi:10.1162/108819803322564361

Holloway, S., & Parrish, K. (2015). The contractor's role in the sustainable construction industry. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 168*(2), 53-60. doi:10.1680/ensu.14.00026

Javernick-Will, A. (2012). Motivating Knowledge Sharing in Engineering and Construction Organizations: Power of Social Motivations. *Journal of Management in Engineering, 28*(2), 193-202. doi:doi:10.1061/(ASCE)ME.1943-5479.0000076

Kam-Biron, M., & Podesto, L. The Growing Role of Wood in Building Sustainability *AEI 2011*.

Kam-Biron, M., & Podesto, L. (2011). The Growing Role of Wood in Building Sustainability *AEI 2011*.

Kibert, C. J. (2016). *Sustainable construction: green building design and delivery*: John Wiley & Sons.

Lamé, G., Leroy, Y., & Yannou, B. (2017). Ecodesign tools in the construction sector: Analyzing usage inadequacies with designers' needs. *Journal of Cleaner Production, 148*, 60-72. doi:https://doi.org/10.1016/j.jclepro.2017.01.173

Minchin, R. E., Li, X., Issa, R. R., & Vargas, G. G. (2013). Comparison of Cost and Time Performance of Design-Build and Design-Bid-Build Delivery Systems in Florida. *Journal of Construction Engineering and Management, 139*(10). doi:doi:10.1061/(ASCE)CO.1943-7862.0000746

Olinzock, M. A., Landis, A. E., Saunders, C. L., Collinge, W. O., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2015). Life cycle assessment use in the North American building community: summary of findings from a 2011/2012 survey. *The International Journal of Life Cycle Assessment, 20*(3), 318-331. doi:10.1007/s11367-014-0834-y

Rodriguez-Nikl, T., Kelley, J., Xiao, Q., Hammer, K., & Tilt, B. (2015). Structural Engineers and Sustainability: An Opinion Survey. *Journal of Professional Issues in Engineering Education and Practice, 141*(3). doi:doi:10.1061/(ASCE)EI.1943-5541.0000228

Said, H., & Berger, L. (2014). Future Trends of Sustainability Design and Analysis in Construction Industry and Academia. *Practice Periodical on Structural Design and Construction, 19*(1), 77-88. doi:doi:10.1061/(ASCE)SC.1943-5576.0000181

Saunders, C. L., Landis, A.E., Mecca, L., Jones, A.K., Schaefer, L.A., Bilec, M.M. (2013). Analyzing the Practice of Life Cycle Assessment: Focus on the Building Sector. *Journal of Industrial Ecology, 17*(5), 777-788. doi: DOI: 10.1111/jiec.12028

Schaufelberger, J., & Cloud, J. (2009). LEED Certification: A Constructor's Perspective *Building a Sustainable Future*.

Sheskin, D. J. (2007). *Handbook of Parametric and Nonparametric Statistical Procedures*: Chapman & Hall/CRC.

U.S. Green Building Council. (2009). LEED Reference Guide for Green Building Design and Construction *Material and Resources*. Washington, D.C.: U.S. Green Building Council.

U.S. Green Building Council. (2013). LEED Reference Guide for Building Design and Construction. Washington, DC: U.S. Green Building Council.

U.S. Green Building Council. (2017, 25 January 2017). Infographic: Top 10 state for LEED in 2016. Retrieved from https://www.usgbc.org/articles/infographic-top-10-states-for-leed-in-2016

Zhong, Y., Ling, F. Y. Y., & Wu, P. (2017). Using Multiple Attribute Value Techinique for the Selection of Structural Frame Material to Acheive Sustainability and Constructability. *Journal of Construction Engineering and Management, 143*(2). doi:https://doi.org/10.1061/(ASCE)CO.1943-7862.0001210

CHAPTER 3 – MODELLING THE CONCEPTUAL DESIGN DECISION PROCESS WITH A SYSTEMS ENGINEERING METHOD

Abstract

Early design decisions (those made during conceptual design) for complex projects are the result of a process comprising a rotating cast of participants, decision making with imperfect information, and multiple communication paths. A change in the earliest decisions impacts the remainder of the design process; for example, selecting a construction material early on restricts the balance of the design process to materials compatible with the construction material selected. Employing systems engineering methods assists design teams in examining complex project processes and the potential impacts of a change to the established process.

This chapter explores how a systems engineering tool, message sequence charts (MSCs), can be used to model the conceptual design decision making process for selecting building materials for use in sustainable building projects. The authors introduced MSCs to two focus groups of experienced architecture and engineering professionals and asked the participants to develop an MSC that documents the conceptual design process for a recently designed building. Then, the focus group participants considered the strategy they thought would be most effective to integrate a new sustainability requirement for building materials, in this case Environmental Product Declarations, into their project, and they documented the adjustments to their specific design process in a modified MSC.

This chapter elucidates how MSCs support the study of complex design processes and how they can identify potential impacts of new sustainability requirements on a standard design process, in turn making explicit the relationship between the design process and the sustainability properties of the building product. This research suggests that the most effective methods to modify the conceptual design process is to engage or employ subject matter experts. In the case of sustainable building materials, specifically, the authors find it beneficial to have an owner with a sustainable building goal from the inception of the project, and to initiate coordination with building material manufacturers. These methods require additional iterations within the design process that are necessary and worthwhile according to the focus group participants, despite the additional time required during early design.

Introduction

Conceptual design is challenging due to the iterations required for development from various sources of uncertainty (Eckert & Clarkson, 2010; Wynn & Eckert, 2017; Yassine, Joglekar, Braha, Eppinger, & Whitney, 2003), and unique characteristics that lead to complexity (O'Donovan, Eckert, Clarkson, & Browning, 2005). A design is successful when the conceptual design can lead to an on-time and on-budget project. Modelling the conceptual design allows for examination of the process to institute potential improvements. For example, Zhang, Hao, and Thomson (2015) model a design process to manage complexity and innovation, and Eisenbart, Gericke, and Blessing (2011) use design models to enhance communication amongst different disciplines. Kobayashi (2005) uses a design support tool to manage the conceptual design process for the product life cycle planning in the eco-design of products.

There are many types of models that have been developed, with each having strengths and weaknesses. This paper will focus on task precedence models, which are event-driven process chains that have been used to examine product development (Smith & Morrow, 1999) and business process (Melão & Pidd, 2000). The general strengths of a task precedence model are they are easily understood, and they allow for flexibility in granularity and applications. Park and Cutkosky (1999) developed the design roadmap approach, a task precedence model, specifically for engineering design processes. Wynn and Clarkson (2017) examine strengths and challenges in design and development models to develop a framework classifying a task precedence model as an analytical type model of meso-level scope. The meso-level model focuses on the end-to-end flows of tasks as the design progresses, and the analytical model provides situation specific insight and improvements based on representing the details of design development process.

This paper uses MSC, a task precedence model, to document an Architecture, Engineering, and Construction (AEC) conceptual design process, with the goal of identifying possible ways to effectively incorporate a new design parameter. An MSC is a graphical language that visualizes communications between systems, stakeholders, or entities (See . This systems engineering tool is a task precedence model that allows for the examination of a defined system, with the boundary defined by the entities selected. MSCs are intuitive to allow for ease for individuals, or groups to complete them for a workflow process (van der Aalst, 2000). MSCs are ideal for examining the conceptual decision process; defining the system, and understanding the communication between multiple participants or groups in sequence. MSCs were selected for their unique ability to show the items transferred, as well as actions of each participant in an intuitive manner, and without software. The strength of this task precedence model is in addition to being able to document the sequence of tasks, it allows for iteration, flexibility between series of tasks, and allows a task to influence the process without producing information.

The paper is organized as follows: The Background section describes how process models have been used to examine the AEC design process and describes the model we will use, as well as the reason it is critical to be able to introduce a new source of environmental information into the conceptual AEC design process. The Case Study section presents the case study method used to transparently document a complex process using MSC, and then the introduction of a new source of environmental product information. The section MSC Results presents MSC and transcript coding procedure and results, as well as discussion. In conclusion, the sections, Limitations and suggestions for future work and Concluding remarks, discuss the potential implications of MSCs for other information in the AEC conceptual design process, as well as the potential for broadening the scope of the use of an MSC for introducing new environmental information into the AEC conceptual design process, as well as the design process of other industries and products.

Background

This research uses a model of the conceptual design process in the AEC industry to determine the most effective way to introduce a new design parameter into the existing design process. In this case, the authors explore how adding sustainability information, specifically, a new source of environmental product information, impacts the design process. A novel task precedence model, the message sequence chart (MSC), supports the modeling of this complex system, in a manner that is accessible to the AEC design team.

Modeling Sustainability in the AEC Design Process

Process models representing workflows and information flows, mainly task precedence models, have been commonly used to study many aspects of the AEC design process. Zanni, Soetanto, and Ruikar (2014) combine two methods of Integrated DEFinition (IDEF) language, to compensate for the weaknesses of each, when creating a process model for a BIM-based sustainable design process for the Royal Institute of British Architects Plan of Work 2013. IDEF0-model is used by G. E. Gibson, Kaczmarowski, and Lore (1995) to document the pre-project planning process for capital facilities. Swimlane diagrams, or cross-functional maps, are process models that use ordered individual task and stakeholders to demonstrate a workflow (Damelio, 2011). Parrish and Regnier (2012) use swimlane diagrams to examine how to support energy savings in existing building retrofit projects by mapping the design process and analyzing how different processes influence energy performance. Macmillan, Steele, Kirby, Spence, and Austin (2002) examined several models to develop a tool for architectural and engineering teams to utilize in conceptual design to manage the process. Klotz, Horman, and Bodenschatz (2007) developed the "Lean and Green protocol" to facilitate the sustainable building delivery process from an owner's perspective, leveraging the IDEF method, swimlane diagrams, and nine other modeling influences.

Sustainability in the AEC industry & Sustainable building materials

In recent years, the AEC industry has grown more interested in green, sustainable, or high performing buildings (HPB). For the purpose of the paper, the authors use HPB, and define it as a building that has been certified, or one whose design was verified by a third party as meeting that third party's specified sustainability requirements.

HPB rating systems are used by the AEC industry, in part, to address the environmental impacts of the construction industry, which has significant material demand with high waste generation. The demand for construction materials has expanded rapidly, increasing 80% from 1980 to 2008, with economic growth closely tied to this demand (OECD, 2015). Additionally, construction and demolition waste accounts for 534 million tons of debris, twice the amount generated from municipal waste (Office of Land and Emergency Management, 2016). Thus, HPB rating systems address both construction materials and construction waste. To address materials, each HPB rating system requires a number of different environmental product information sources to satisfy the certification requirements for pertinent building materials. Similarly, HPB rating systems offer points for recycling construction materials during demolition and construction activities (Green Building Initiative, 2016b; U.S. Green Building Council, 2013). The rating systems have been updated over the years, with new versions pushing for greater reductions in the environmental impact from building materials specifically, as well as from the building as a whole. Two HPB rating systems, the U. S Green Building Council's Leadership in Energy in Environmental Design (LEED) and the Green Building Initiative's Green Globes, have introduced Environment Product Declarations (EPD) as a source of information for the environmental impact of building materials (Green Building Initiative, 2016b; U.S. Green Building Council, 2013).

An EPD communicates verified, transparent, and comparable information about the lifecycle environmental impacts of product. At the time of this publication, EPDs are registered for approximately 800 products in 13 categories with the International EPD® System, ranging from food to fuel to services. The "Construction Products" category comprises 445 EPDs, including EPDs for structural steel, light fittings, plumbing fixtures, various wall, floor and ceiling finishes, and many other building materials (EPD International AB, 2017). Due to the expansion of EPD offerings, as well as their increased discussion in HPB rating systems, this paper uses EPDs as a canonical example of how sustainability information can be added into the existing conceptual design process. In particular, this paper examines the ways AEC teams believe EPDs can be introduced into the design process most effectively.

Project Delivery Systems

There are several different contractual arrangements, so-called project delivery methods, for the design and construction of a building. Each delivery method demands different relationships between the involved parties, and each has different benefits and challenges. This paper considers conceptual design in two different delivery methods; namely, Design bid build (DBB) and Design-build (DB).

DBB was the most commonly employed delivery method for much of the twentieth century, and it was heralded as a system that delivered a project to the owner with lowest costs due to the competition it fostered between builders. In a DBB system, the owner hires a design team to produce a building design on behalf of the owner. This design is then "sent out for bid," at which point, general contractors bid on the project. The qualified bidder offering the lowest price receives the contract to build the building (Hale, Shrestha, Gibson, & Migliaccio, 2009; Kibert, 2016).

DB delivers a project with one entity, the design build team, working under a single contract with the owner to provide design and construction services. DB has increased in popularity in the US over the past 15 years (Design-Build Institute of America, 2018). DB seeks to combine the competitive advantages of DBB with benefits resulting from creating a single team to deliver both design and construction. In a DB scenario, the owner still "shops" for the lowest price to complete their project, but rather than only selecting the lowest-priced builder, the owner interviews teams of designers and builders and selects the lowest-priced team that is also qualified to complete the project. In requiring designers and builders to work together from the design phase of the project, owners expect that designs will be more efficient to build and builders will address constructability concerns during the design phase, when changes are less costly.

AEC Conceptual Design

Dependent on the project delivery method, the conceptual design process for a building differs in the parties involved and their relationship to each other. Common elements of a building conceptual design include the basis of design, a document that outlines the planned functionality of the building; a feasibility study, that considers the financial viability of the project, such as risk analysis and return on investment; and a set of potential building designs. In all cases, the goal of the conceptual design phase is to merge the building owner's needs and wants with corresponding physical space.

Well informed conceptual designs are commonly recognized as critical to the overall success of the design and construction of a building project (George E Gibson & Hamilton, 1994; Mollaoglu-Korkmaz, Swarup, & Riley, 2013). Further, engaging a multi-disciplinary design team that collaborates early in the design process contributes to the success factors for HPBs (Lapinski, Horman, & Riley, 2006; Li, Chen, Chew, Teo, & Ding, 2011; Magent, Korkmaz, Klotz, & Riley, 2009; Robichaud & Anantatmula, 2011). Just as integration amongst designers during conceptual design contributes to successful projects, it is likely that integration of material design decisions during conceptual design will contribute to the success of HPBs.

Case Study

This research asks focus group participants to use MSC to model the conceptual AEC design process to determine the most effective way to introduce EPDs into the existing design process.

Context

The authors will discuss the results from one of the project delivery types, design build, which all also had the same type of owner, the federal government, in detail to understand the efficacy of MSCs for modeling the introduction of EPDs into a conceptual building design process. Similar discussions could involve the data and process collected for the projects delivered via design bid build, or with a university or private owner.

Focus Group Background

Focus group sessions were designed to mimic the design charrette scenario, a common conceptual design team meeting used to make interdisciplinary design decisions (G. Edward Gibson & Whittington, 2010). The focus groups convened design teams in their office setting. Two geographically diverse full-service Architecture & Engineering firms were recruited to participate in the focus groups. The research methodology is presented in Figure 9. The authors facilitated the focus groups.

Focus group participants were required to be familiar with each other, and would have ideally worked as a project team previously. Additionally, focus group respondents were requested to "have a working knowledge (and preferably been a participant on) at least one HPB project, have familiarity with the general design process and any nuances associated with the HPB design process, as well as the specification writing process".

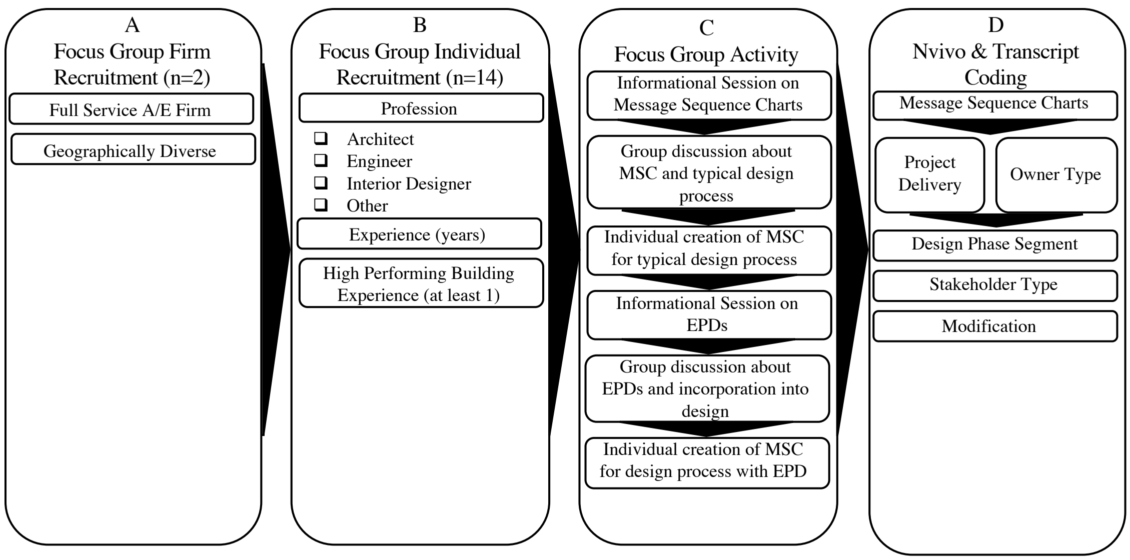


Figure 9. Focus group data collection methodology

One of the firms that participated has 201-500 employees, and other firm has more than 1500 employees. Table 7 displays the focus group participant demographics. Respondents completed a consent form and a survey about their experience with environmental product information for building materials in the design process (Burke, Parrish, & Asmar, 2018) prior to the focus group.

Table 7. Discipline and industry experience of focus group participants

Focus Group Demographics (n=14)			
Discipline		Industry Experience (Years)	
Architect	7	< 2	0
Engineer	4	2 - 5	3
Interior Designer	3	5 - 10	2
		10 - 20	8
		> 20	1

MSC Data Collection in Focus groups

The focus group sessions were scheduled for two hours and were video recorded. There were two parts to the session, each part having an introductory presentation with discussion and questions, and an exercise for the participants to complete. Participants were given an example MSC, and two blank MSCs. The first part of the focus group introduced participants to MSCs, describing how an MSC can show a process, including the stakeholders involved, the sequence of events, and the item(s) transferred. Participants were asked to think of a specific project they had recently worked on, and note the specifics of it, i.e., type of client (e.g., government, university, private), delivery method used (e.g., design-build, design-bid-build), and any other important project descriptors. This MSC documented the actual material selection process used during conceptual design for the participant's project. Participants were encouraged to ask questions and discuss their ideas; however, they were asked to individually create an MSC that illustrated the material selection process from their perspective.

The second part of each of the focus groups described the current state of the practice for sources and use of environmental product information in the AEC industry. The participants were introduced to EPDs. There was a round of discussion to encourage a full understanding of EPD, how they are used, and the participant's familiarity with them. The authors then asked the participants to create a second MSC showing the best method to incorporate environmental product information (EPDs or other sources) into the material selection process they documented in the first part of the group. Again, the authors encouraged the participants to discuss how to modify their process, but each participant was asked to individually document the material selection process, in order to capture their perspective.

Analysis

The original, and modified MSCs (n=28) for each participant, and the transcripts of the focus groups were uploaded to a qualitative data analysis tool, NVivo. NVivo has been used to code and analyze qualitative data in previous AEC industry studies (e.g., (Javernick-Will, 2012; Rodriguez-Nikl et al., 2015)). The software allows the authors to manage the data and create queries within the qualitative data with reference to all of the themes ("nodes" in NVivo) created by the authors. These themes created the coding used on the focus group data collected, discussed in sections MSC Coding Procedure and Transcript Coding Procedure.

MSC Results

The authors performed several layers of coding of both the MSCs and the focus group transcripts. This supported exploration of the many different project characteristics, while also examining the design process sequences each individual focus group documented. Moreover, the multi-layer coding allowed the authors to find convergence around strategies for incorporating environmental product information into the material selection process and into the conceptual design process more broadly. These layers of coding are described in detail below, and demonstrate an approach that could be mimicked for other design processes and industries.

MSC Coding Procedure

The authors inductively developed three coding schemes in the MSC analysis, each with different themes. These coding schemes were initially developed as the authors completed two rounds of reviews of the MSCs. In each of the two rounds, the MSC were grouped based upon the given descriptors for project delivery type and building owner type (Table 8). During this grouping, patterns were observed in the MSC stakeholders recorded, the sequence of transfers of information between stakeholders, and the changes between the standard design process and the modified process.

Table 8. Project delivery type and building owner type for the 14 projects. One focus group selected to all document the same project which resulted in the seven design bid build projects with a University owner, this paper focuses canonically on four design build, governmental owned conceptual design processes

Project Delivery \ Owner Type	Governmental	University	Private
Design Build	4	1	1
Design Bid Build	0	7	1

Table 9. Stakeholder type code for all MSC collected from the focus group participants

Stakeholder Type Code	
Category	*Description*
Shareholder/User	Occupant of the building, may also be the owner; provides data about the needs
Client	AE design team has a contractual relationship with client; may be the contractor or owner; provides direction to the AE design team
AE Design Team	Architects, engineers, interior designers, and planners; this group of stakeholders coordinates to provide the building design to the client
Subject Matter Expert	Provides guidance in reference to HPB; may be in-house to the AE design team or an outside consultant
Owner	Owns the building; may also be the client or shareholder/user; provides finances
Equipment Vendor/Material Manufacturer	Building material and equipment provider; provides information for design development
Contractor	May be the client; constructs the building; procures building materials

The initial set of stakeholder codes listed every stakeholder that appeared on an MSC document collected in the focus groups. This originally included 27 different stakeholder names. These stakeholder codes were adjusted through interaction with the data and aimed to capture the nuanced terminology used to describe design process participants. Descriptions of the codes were developed to ensure all stakeholders were accurately coded and representative across the project delivery types and building owner types. Table 9 displays the final resulting stakeholder type coding.

An MSC supports documentation of iteration and flexibility between a series of tasks. This is accomplished by breaking an MSC up into segments that illustrate different events in the design process. The authors created segmentation as follows: the segments shall not be repetitive within themselves, a segment should have a maximum of 4-5 stakeholders, and the segment should have a maximum of six item or information transfers. The authors segmented each of the 28 MSCs according to these guidelines. Each of the 28 conceptual design MSCs (14 original, and 14 modified) included between 4 and 9 distinct segments. The authors grouped MSCs according to project delivery type and building owner type. This grouping helped to identify the segments that repeat in all of the conceptual design process MSCs. Table 10 lists the final Design Phase segment codes resulting from the segmentation and grouping exercises.

The third coding scheme developed indicated the modification a focus group participant made between the initial conceptual design process MSC and the modified MSC created when they were asked to incorporate EPDs into the process in the manner, they thought would be, most effective. The coding of the transcripts, discussed in

Transcript Coding Procedure, also confirmed and heavily influenced the final coding of the suggested modifications code and their descriptions (Table 11).

Table 10. Final design phase codes for all MSC (n=14) collected from the focus group participants

Design Phase Segment Code		
Category	*Description*	*Segment Label in MSC (Fig 2 – Fig 4)*
Project Initiation	Includes a recognition of need, solicitation of services, contract	1a, 1b
Design Concept Development	Initial conceptual design	2a, 2b
Design Concept Finalization	Further iteration of concept, includes the shareholder/user	3a, 3b
Engage Material Manufacturer/ Equipment Vendors	Limited information required from vendor/manufacturer	4a, 4b

Table 11. Modification code for the MSC and transcripts collected from the focus group participants

Suggested Modification Code (initially from MSC, confirmed in transcripts)	
Category	*Description*
Engage additional stakeholder	MSC segment is equivalent except an added stakeholder to the same sequence
Additional iterations	A segment is repeated in the second MSC, and was not in the initial MSC
Additional Modification Influence Code (from transcripts)	
Owner	HPB (and then EPD) required per owner, hopefully early in the design process
Visibility of Project	Flagship or headquarters, HPB requirement is often an add on later in the design process
Mandated	HPB required per code or federal mandate, is usually known early in the design process

Transcript Coding Procedure

Simultaneous to the coding of the MSC charts, the authors transcribed the focus group audio. During the transcription, notes were made of the category codes created for the MSC coding. Whenever *stakeholder type*, *phase breakdown*, or *modification* was discussed, it was coded in the transcript in Nvivo. The category coding for *stakeholder type* was verified, and additional description and clarification was provided for the stakeholders that have multiple roles. For example, it was verified that the *user* may also be the *owner* based upon the building owner type, and the *client* could either be the *contractor* or *owner*, dependent upon the project delivery type. Design phase segment coding was not influenced by the transcripts.

The next step examined the transcripts that were marked with a code, and determine if this category code is reflected in some manner in the MSC documents. For instance, there was a conversation between the focus group participants regarding the engagement of a material manufacturer or equipment vendor, and this has been reflected in the MSCs through a new sequence being added in the modified MSC that engages this new stakeholder. However, there are several discussions about the owner requiring the HPB certification, but this does not appear as a new "design phase segment" code, or through a "suggested modification" code of the "engage additional stakeholder", as the owner is already engaged in the design process. For this instance, there were several locations in the coded design phase segments where an item or information transfer was indicated to have an alternative, or additional requirement, by at least one of the focus group participants (indicated by * in Figure 10-Figure 13).

MSC and Transcript Coding Results

This section is devoted to discussing the results of the MSC and transcript coding process to demonstrate the opportunities for replicability in other processes and industries. In particular, the discussion focuses on the results from the MSCs for the four government owner, design build projects that were provided by the focus group participants. Individual results from this category of projects will be described, with attention paid to the features that may be replicated.

MSCs are read with time going down the page, the stakeholders that participate in that segment across the top, and arrows representing the transfer of ideas, information, or an item from one stakeholder to another, with a description of the transfer indicated on the arrow. The hollow box on a stakeholder line indicates an action performed by that stakeholder, and a box connecting more than one stakeholder indicates an action that is iterative between the stakeholders, with the stakeholders involved indicated by the solid box on that stakeholders line. The segments on the left (indicated with a) are representative of segments in the original design process. The segments on the right (indicated with b) are representative of the same segment with modifications (clouded) the focus group participants made to the design process once EPDs were introduced as a source of information in the design process. You will find a brief description developed for each of these segments in Table 10.

To arrive at each of the common segments, the authors followed three steps. First each of the four MSCs were broken up into appropriate segments, resulting in 31 different segments. Next, the authors grouped together the segments from each MSC with the same stakeholders involved, independent of when they occurred in each MSC, and began to compare the actions performed and transfers initiating at each stakeholder, looking for commonalities. This step also involved refinement of the stakeholders type code, accounting for the nuanced names used by the different focus group participants. For example, shareholder/user in the government owner, DB projects (Table 9) were also known as building occupant, end user, and tenant. Rough grouping of the segments showed significant commonalities in the segments, and in the overall MSC, although the order and number of segments varied, and there were some differences that could be easily identified. The last step in creating the common segments for each project delivery and owner type grouping, was to draw each MSC segment, indicting where and what the nuanced differences were. Figure 10, Figure 11, Figure 12, and Figure 13 illustrate the eight distinct segments that resulted from coding the four government owner, DB MSCs.

The occurrence and sequence of the coded segments that make up each of the MSC as reported by the focus group participants are shown in Table 12. Focus group participant A3-12, an architect with 12 years industry experience, has documented the inclusion of a new segment (4b, Figure 13) as the most effective way to introduce an EPD into the conceptual design. The inclusion of this segment engaged a new stakeholder, the subject matter expert, in the design process, and also engaged the equipment vendor or material manufacturer in the conceptual design process, both providing information and feedback that was absent in the original design process MSC. Focus group participant I1-06, an interior designer with six years industry experience, suggested a new team member should be engaged from the project initiation, demonstrated by a change in the first segment (1a to 1b, Figure 10), as well as all of the following segments. There is an * by segment 1b (Table 12) as the focus group participant discussed the importance of the shareholder/user's commitment to the HPB certification at this phase for the best opportunity to have a successful project with minimal redesign.

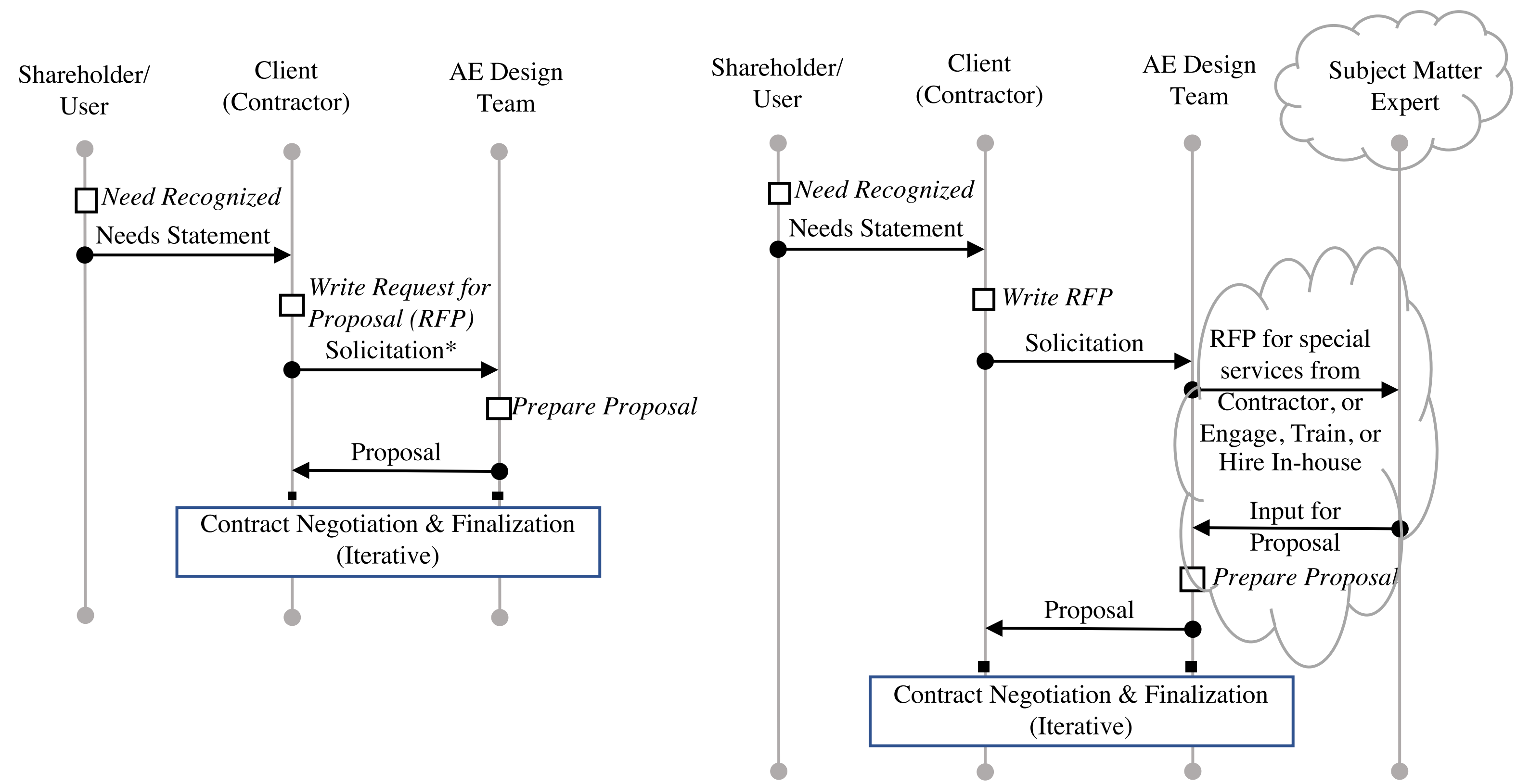


Figure 10. Coded project initiation message sequence chart segments, original (1a, left), potential modification (1b, right)

** indicates where (at least) one of the focus group participants indicated in the transcript there should be a modification*

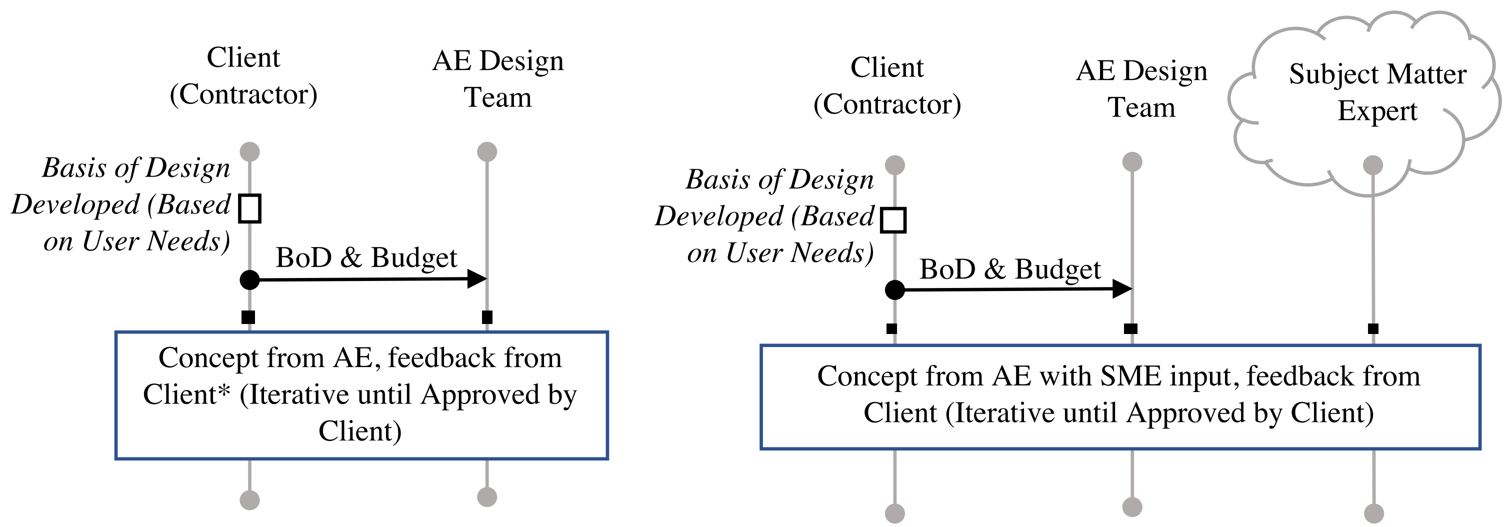


Figure 11. *Coded design concept development message sequence chart segments, original (2a, left), potential modification (2b, right)*

** indicates where (at least) one of the focus group participants indicated in the transcript there should be a modification to the design process, although it was not reflected on the MSC document they created.*

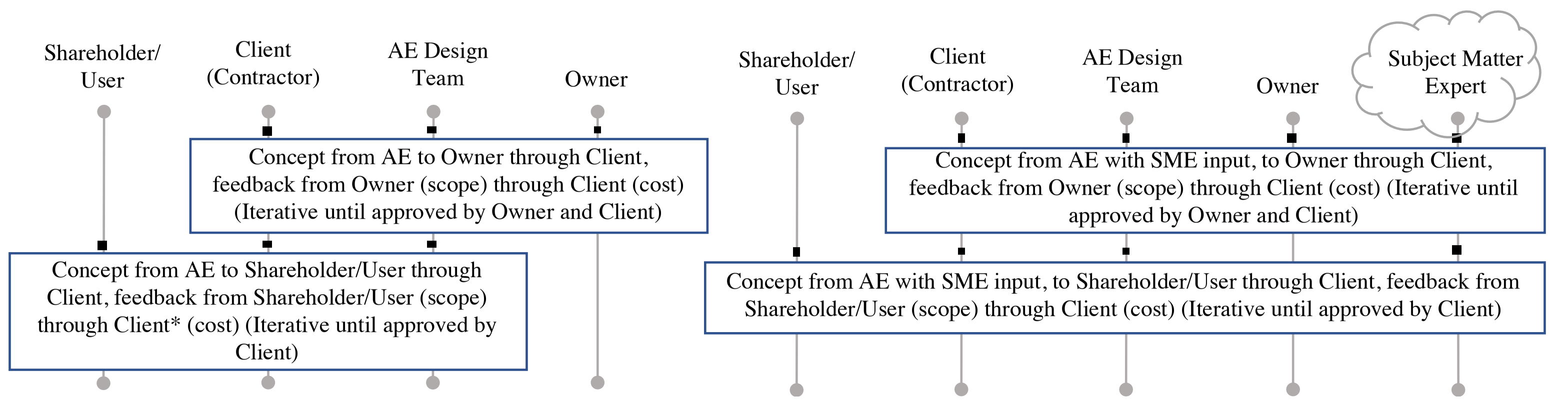


Figure 12. Coded design concept finalization message sequence chart segments, original (3a, left), potential modification (3b, right)

** indicates where (at least) one of the focus group participants indicated in the transcript there should be a modification to the design process, although it was not reflected on the MSC document they created.*

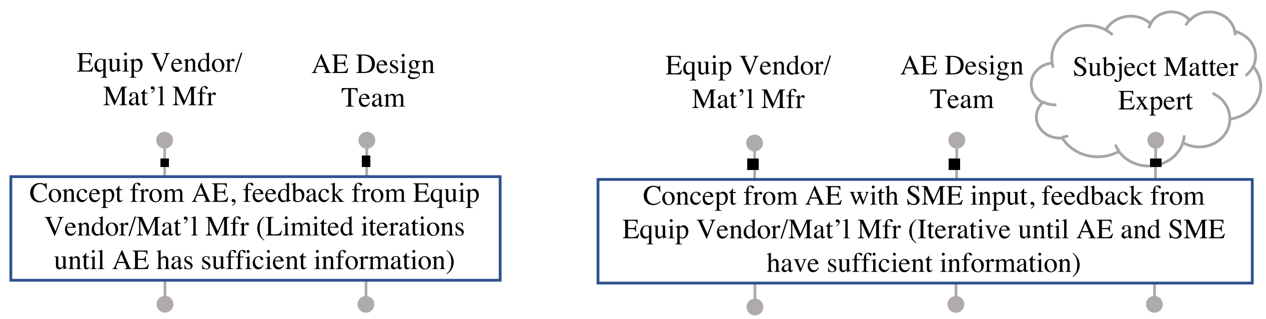


Figure 13. *Coded engage material manufacturers and equipment vendors message sequence chart segments, original (4a, left), potential modification (4b, right)*

*Table 12. Occurrence and sequence of the segments for each of the four coded government owner, design build message sequence charts. Shaded cells indicate the change in the process that was indicated on the participants second MSC that corresponded to the introduction of EPDs in the design process. * indicates a difference in the actual sequence from the coded sequence documented in Figure 10, Figure 11, Figure 12, or Figure 13.*

	Focus Group Member							
	A3-12		I1-06		E1-15		A2-10	
Sequence	Standard Process	With New Information	Standard Process	With New Information	Standard Process	With New Information	Standard Process	With New Information
1	1a	1a	1a	1b *	1a	1a *	1a	1a
2	1a	1a	2a	2b	3a	3a	1a	1a
3	2a	2a	3a	3b	4a	4a	2a	4b *
4	2a	2a	3a	3b	3a	4b *	3a	2a
5	3a	4b	--	--	--	3a	--	3a
6	3a	3a	--	--	--	--	--	--
7	--	3a	--	--	--	--	--	--

Discussion

The coding methods and insights provided in the sections MSC Coding Procedure, Transcript Coding Procedure, and MSC and Transcript Coding Results are based on focus group work completed with two AEC firms, and are specific to that context. Nevertheless, some of the layers of design process complexity were modeled in a manner that could be replicated for other processes and industries. For instance, the use of MSCs allowed for flexibility in the coded segments to be consistent across different project delivery types and to demonstrate multiple instances and varying levels of iteration, as well as the ability to easily identify several specific strategies for a modification. MSCs present a strategy to manage these common challenges in modelling design processes. Additionally, MSCs allowed the authors to determine the best method to incorporate a new source of environmental information into the design process, an issue that a large proportion of product and process design teams are currently grappling with in some manner, as environmental considerations become more prominent across engineering disciplines.

The modelling method described within, using design teams as focus groups to collect MSCs that in turn support exploration of a modification to the design process, proved to be effective for this specific situation. The authors were able to thoroughly explore the AEC practitioners' suggested strategies for incorporating EPDs into their conceptual design. The coding process for MSCs demonstrated a way to manage a large number of stakeholders and easily illustrate design process iterations, while creating representative design sequence segments that allow for a flexible task sequence model. Then the coding of the associated transcripts allowed for a deeper understanding of the underlying motivations for changes recorded in the MSC. Ultimately, this process allowed the authors to thoroughly examine each of the layers of complexity in the design process.

While this research focused on a new information source used by the AEC industry, the information source could be used by other engineering disciplines as well, as EPDs cover more products than construction materials. Moreover, the methods described for MSC development, as well as MSC coding and analysis, can be used to explore other industries and processes where the design team is interested in understanding how new information or a change in a design process may affect the project.

The project delivery method modelled in this paper, design build, is considered an alternative project delivery method; however, comparable analysis and deduction have been completed for the traditional project delivery method, design bid build. The authors were able to use many of the same design segment codes, or very similar design segments, when modelling the traditional delivery method. The MSCs ability to model various project delivery methods is desirable as it can highlight the complexities unique to different project delivery systems. Thus, MSCs support improved understanding of the changes required in the design team approach, or how to effectively change the communication tools used by the design team, in order to achieve the same outcomes. The alternative project delivery example used in this paper suggests the MSC may be a design process modelling method that is generalizable for other non-traditional design processes.

Implications for the AEC industry

This chapter primarily focused on the coding results of eight of the 28 total MSC collected in two AEC focus groups for canonical purposes. The broader results for the AEC industry are contained in Table 11, which shows the strategies that emerged in the coding of the entirety of the collected MSC. Engaging an additional stakeholder with a depth of familiarity of MSC was the most frequent strategy that emerged from the focus groups, followed by early commitment by the owner to the use of EPDs in the design, or to the HPB rating system that requires them.

Limitations and suggestions for future work

This research leveraged a small convenience sample of fourteen design team participants comprising two separate design teams. Both teams already had high performance building experience, which may skew their MSCs to suggest that relatively little change would be required in the design process to accommodate a new source of sustainability information. Moreover, these experienced teams used a project delivery system that is arguably more conducive to incorporating sustainability information into the design process, so this may also make the MSCs presented in this paper less applicable to other engineering disciplines. Despite these limitations, this work illustrated the efficacy of an MSC for illustrating how sustainability information can change a design process.

At the conclusion of this study, the authors identified opportunities for future research. This research as focused specifically on utilizing a new information source to inform the AEC conceptual design process. This is directly incorporating a new focus, sustainability, into a process that is already very complex. Each of the different strategies that have emerged from this modelling could be examined as well. For example, this approach could be used to examine other sources of complexity that emerge without the new focus. For example, MSCs could be used to examine the impact of engaging new projects team members, or engaging current project team members earlier in the process.

Finally, the AEC industry, as well as many other industries, have several other new environmental data sources that are becoming more prevalent, such as life cycle assessments, and health product declarations. MSCs, and the associated coding process, can be used to examine the most effective strategies for incorporation of these data sources into the AEC design process, as well as the other product design processes that may benefit from incorporating these new information sources.

Concluding remarks

This paper examined how to model potential strategies for introduction of an emerging information source into conceptual design. In particular, this paper presented an example of incorporating the EPD into the conceptual building design process. This paper illustrated the efficacy of MSCs, a task precedence model used in systems engineering, for documenting design processes. An MSC allows for scalability, flexibility in the order of discrete segments, iteration, and a method to thoroughly examine the layers of complexity that emerge from a design process.

The use of focus groups for data collection, and the coding technique described within, was selected based on its alignment to existing practices in the AEC industry. It is only one example of how an MSC can be used to analyze ideas about design processes and their modifications to find convergence among a design team. The analysis of the design team's conversations about their conceptual design process strengthened the findings from the MSC analysis; as such, it confirms the findings for this particular design process and for the abilities of the MSC.

Several strategies were identified by the focus group participants as successful strategies to incorporating EPDs into the conceptual design process. Owner commitment to a HPB early in the design process, and the addition of a subject matter expert in MSC as a new team member were thought to be the most critical to the successful use of EPD to inform the design process.

CHAPTER 4 – TOWARDS DISPELLING SUSTAINABLE CONSTRUCTION MYTHS: A CASE STUDY APPROACH

Abstract

The architecture, engineering, and construction research has substantiated a number of beneficial effects of an owner's early commitment to a construction project, and continued involvement through construction. Additionally, previous research (Chapter 3) illustrates that the owner's commitment to a high performance, green, or sustainable building (HPB) certification, realized early in the design, may also contribute to projects achieving higher levels of certification, without a cost premium. This research examines, through 19 case study projects, the impact of three different project characteristics on the design team's approach to considering environmental product information during design of an HPB. In particular, the research explores the effect of: (1) the owner's commitment to an HPB certification, (2) the engagement of a consultant early in the design process, and (3) the review of environmental product information for building materials early in the design process. This research examine how these variables impact the *design approach*, as indicated by accessing different sources of environmental information for building materials and including designers with HPB training on the design team, as well as the *design outcome*, defined as the level of certification achieved. This research illustrates that an owner's commitment to an HPB certification and the review of environmental product information both have an impact on the project outcome, while they also both impact the design approach.

Introduction

High performance building construction accounts for approximately 33% of projects, as reported by Architecture, Engineering, and Construction (AEC) firms in 2015 (Buckley & Logan, 2016). Leadership in Energy and Environmental Design (LEED), established by the U.S Green Building Council in the late 1990s, and other high-performance building (HPB) certifications, seek to curtail the environmental impacts of the AEC industry, as well as improve and promote the health and comfort of building occupants. Building materials represent one aspect of a building's environmental impact, as reflected in HPB certification systems, as are the building location and site, energy use, water use, and indoor air quality. Building material manufacturers have responded to the AEC industry and HPB certification systems' requests for environmental information about their products with a growing number of sources of information. Buildings use 40% of raw materials globally, and building related construction and demolition contributed 160 million tons of waste in the US in 2007 (U.S. Environmental Protection Agency, 2007). Additionally, the average person in the US and Canada spends nearly 90% of every day indoors (Klepeis et al., 2001), where they are exposed to pollutants at concentrations higher than outdoors (Reff et al., 2005).

This research examines the impacts of three different project characteristics in 19 building project case studies to determine if they have an impact on the design team approach, which is measured as (1) accessing different sources of environmental information for building materials and (2) having a higher percentage of the design team with training specific to a HPB, and the project outcome, which is defined as the level of HPB certification achieved. It is predicted that three project characteristics would impact the design approach and outcome, namely: (1) the owner's commitment to an HPB certification, (2) the engagement of a consultant early in the design process, and (3) the review of environmental product information for building materials early in the design process. AEC research (Azhar, 2011; Burke et al., 2018; Zimina, Ballard, & Pasquire, 2012) anecdotally suggests that these three variables would impact the design approach and outcome, and this study tests these hypotheses. AEC practitioners suggest early review of a new environmental product information source is important to inform the design process and the project's HPB certification outcome (Burke et al., 2018). Azhar (2011) studied four case study projects utilizing building information modeling (BIM), a technology that was in its formative stage, to determine if use of the technology early in the design, amongst other factors, is important to successful implementation. Additionally, trained BIM operators were cited as a critical technical hurdle to overcome for widespread adoption by the AEC industry. Target Value Design (TVD) is a proposed project delivery system by Zimina et al. (2012) that engages the owner as active member of the team to successfully deliver challenging projects.

The study presented herein tests the hypotheses that owner commitment, having a consultant on the design team, and reviewing environmental information early in the design process all impact the design approach. Moreover, it is hypothesized that owner commitment and reviewing environmental information early in the design process impact the design outcome. Note these variables are treated as independent during this study; however, the interaction effects of the variables are discussed in this chapter. Finally, the paper concludes with a discussion of potential future directions for this work.

Background

The U.S. Green Building Council's (USGBC) LEED rating system certified 3,366 projects in 2016, accounting for the majority of buildings certified as high performing in the US (U.S. Green Building Council, 2017). The initial public version of LEED, released in 2000, included 18 points for eight different credits related to sustainable building materials, which accounted for 26% of the total points available. For the purposes of this paper, this includes all of the available credits within the "Materials and Resources" credit category, and the "Low-Emitting Materials" credits within the "Indoor Environmental Quality" credit category. In order to earn these credits, designers were required to produce environmental product information describing recycled content, regional materials, renewable resources, certified wood declarations, and volatile organic compound (VOC) content (Building Design & Construction, 2003). Despite changes to LEED over time, this same documentation still supports earning LEED credits related to building materials.

Credits related to building materials accounted for up to 20% of the total available points in USGBC's LEED 2009 (aka LEED v3) for New Construction, first available in April 2009 (U.S. Green Building Council, 2009). This 20% was maintained in USGBC's newest version of LEED, LEED v4, released in November 2013. The updates in LEED v4 were heavily focused in the credits related to building material selection, and included the addition of several new paths to credit achievement, in addition to the paths that were available in previous versions (U.S. Green Building Council, 2013). For example, LEED v4 introduced Cradle to Cradle (C2C) certification, life cycle assessment (LCA), and Environmental Product Declarations (EPD) to the building material credit requirements.

That is, in order to earn one of the new available building material credits, design teams may review C2C, LCA, and EPD for applicable materials, as well receive additional credits by reviewing the information used in previous versions.

Previous work by the researchers has suggested owner commitment to the HPB process, reviewing environmental product information “early,” and the employment of a subject matter expert, or an outside consultant will lead to a more successful HPB. The following hypotheses are tested:

H1: Owner commitment to achieving HPB certification influences the design approach and increases the level of HPB certification (i.e., the project outcome). Thus, it is expected that on projects where the owner commits to an HPB certification, design teams review more advanced sources of environmental product information and include more members with HPB training.

H2: The engagement of an HPB consultant early in the design process influences the design approach and increases the level of the certification. It is expected that when a design team employs an HPB consultant early, design teams review more advanced sources of environmental product information and include less members with HPB training.

H3: Design teams that review environmental product “early” in the design process will have a different design process and higher levels of certification than those that review the information later in the design process. It is expected that when a team reviews environmental product information early, they will use more advanced sources of information, and the team will comprise of more members that have HPB training.

Research Method

This section describes the development of the survey administered to collect case study data for this research, the data collection process, and the case study and quantitative data analysis methods.

Case Study Survey

A multiple-case design was selected to test the aforementioned hypotheses. A survey was developed to collect data about HPB projects. Previous research (Burke et al., 2018) documents strategies AEC practitioners believe would lead to utilization of new environmental product information sources that would inform decisions about building materials. The survey developed for this research aims to examine if these strategies are, in fact, leading to differences in the design process, and the HPB project outcome. Specifically, the data collected was about completed HPB projects. Multiple-case design (i.e., (Yin, 2014)) allows the testing of each of the hypotheses through finding replication logic among the cases that do and do not exhibit the trait of interest (owner involvement, subject matter expertise, and early access of environmental product information).

Surveys were sent to all respondents from a previous survey who indicated they had utilized environmental product information for building materials in their design process, and also indicated it was acceptable to contact them for additional feedback, a total of 32 people. Nineteen project case studies were received from 15 respondents, corresponding to a 47% response rate.

The survey consisted of 4 sections: (1) project background information (Questions 1-8, Table 13), (2) HPB certification and goals (Questions 9-10,Table 13), (3) HPB design, team details (Questions 11-14, Table 13), and (4) environmental product information used (Questions 15-17, Table 13). Table 13 displays the survey questions and possible responses.

Case study projects were only solicited that met the following criteria: (1) project is owner-occupied, (2) project is *not* primarily special use (such as laboratory or assembly buildings), (3) project's total installed cost ranges from $150/SF and $400/SF, and (4) project design team utilized environmental product information (from any source) in the design process. The survey was conditional, and had a note on question 4 (Table 13) to ensure all projects were owner occupied; if the respondent answered "no", they were brought to the end of the survey, and asked to select a different project that met all the requirements to complete the survey.

Data Collection

Once the survey was developed, it was administered online via Qualtrics and data was collected. The 19 project case studies totaled $500M in project costs, and over 1.6M SF of total building area. Table 14 displays the owner types, the building uses, and the project delivery type reported for each of the case studies. The "other" owner types reported were "health system" and two respondents stated "other" referred to "3rd party asset management". The "other" building uses reported were "fire station" and "courthouse". The average total installed cost of the case study projects is $26.3M, with the lowest and highest cost projects reported as $1.8M and $81M, respectively. The average total building square footage is 84,313 SF, with the largest and smallest area as 225,000 SF and 9,000 SF respectively. The average cost per square foot of the case study projects is $312/SF.

Table 13. Survey questions and responses

	Question	Possible Responses					
1.	Name or title of project (or pseudonym)						
2.	Location of the project (City, State or City, Country)						
3.	Owner	K-12	University	Commercial	Governmental	Other (please describe)	
4.	Owner Occupied (or Primary Client Occupied)	Yes			No		
5.	Building Use/Type	School/ University		Office	Commercial	Other (please describe)	
6.	Total Cost ($MM)						
7.	Total Building Area (SF)	(Note: projects should be between $150/SF and $400/SF)					
8.	Project Delivery Type	Design Build	Design Bid Build	Construction Management at Risk	Multi-Prime	Integrated Project Delivery	Other (Please describe)
9.	Did the project have high-performance certification goals or requirements?	Yes, entirely driven by the client; Yes, but at least partially driven by state, local, or organizational requirements; No					
10.	What was the certification goal or requirement?	(Note: please provide the rating system and level, i.e. LEED 2009 Silver, Green Globes 2 Globes, Energy Petal of Living Building)					
11.	How many design team members were involved in the project at ~35% completion or design development phase?	(Note: include consultants, but exclude the client and/or owner representative)					
12.	How many of the design team at 35% have specific training for the design of high performing buildings?	(Note: i.e., LEED AP (+ Specialty), energy modeling, LCA, etc.)					
13.	What is the specific training the project's design team member have for the design of high performing buildings?	Number of team members: 1	2	3	4+		
		LEED AP+ Specialty					
		LEED AP					
		Energy Modeling					
		Life cycle assessment tools (i.e., Athena, Gabi, etc.)					
		Other (Please describe)					
14.	Did the design team have a hired sustainability consult on the project at ~35% completion or design development phase (i.e., leads sustainability focus, manages the certification process, energy modeling, etc)?	Yes	Yes, but engaged later in the design process	No			
15.	At what phase in the design process did your team first review any environmental product information for any of the building materials? (i.e., recycled content, certified wood, VOC content, EPDs, etc.)	~0-10% (Pre-design)	~10-35% (Design development)	~35-65%	~65-90% (Pre-final)	~90-100% (Construction Documents)	After construction documents
16.	What environmental product information was accessed (in any way) on the project prior to 35% completion or design development phase? (select all that are applicable)	Recycled Material Content (RC)	Regional Material Content (RegC)	Renewable Resource Content (RRC)	Certified Wood Declarations (CWD)	Environmental Product Declarations (EPDs)	
		Volatile Organic Compound (VOC) Content	Cradle to cradle (C2C) Certificates	Life cycle assessment (LCA) reports, calculators, software	Other (Please describe)	None	
17.	Did reviewing any of this environmental product information change any of the building material selections, OR was this information a primary factor in selecting any materials?	Yes	Not sure	No			

Table 14. Owner type, building use, and project delivery type reported for the 19 case studies

Owner Type		Building Use		Project Delivery Type	
University	6	Office	7	Design Bid Build	6
Governmental	4	School/ University	10	Design Build	7
K-12	4	Other	2	Construction Manager at Risk	6
Commercial	2				
Other	3				

The survey allowed respondents to select a project with the recognized HPB certification of their choice, however they only provided information about projects that are LEED certified.

The survey was sent to practitioners across the United States. However, nearly all data provided in this survey comprised projects located in the mid-Atlantic region of the US, with only three projects reported outside that region: two in Cincinnati, Ohio, and one in Houston, Texas.

Data Analysis

The collected data was sorted corresponding to each of the hypotheses that was being testing: owner demand, consultant on design team, and accessing the information early in the design (Table 15). Case study analysis was conducted for each of the hypotheses independently. Within that context, the same three dependent variables were examined for replication, two examining the project approach, and one examining the project outcome, within the sorted data for the case studies.

Table 15. Independent variables and dependent variables examined on the case studies

Dependent Variables		Case Study Lens, Independent Variables		
		Owner Demand	Consultant on Team	Accessing Information Early in Design
	Approach	Sources of Information used	Sources of Information used	Sources of Information used
	Approach	Number of HPB trained professionals on the design team	Number of HPB trained professionals on the design team	Number of HPB trained professionals on the design team
	Outcome	Certification Level	Certification Level	Certification Level

The responses to the questions 9, 14, and 15 (Table 13) were categorized into nominal variable responses, and were analyzed with Fisher's exact test of independence. This statistical analysis method determined if the proportions of one variable were different depending on the value of the other, and was most appropriate for the small sample size (David J Sheskin, 2007). However, limited statistical significance was established, and as stated in the limitations and future work this research should be expanded, in numbers, and geographically, to be able to infer broader applicability.

Results & Discussion

The results and discussion section will examine each of the case study contexts corresponding to a hypothesis, and then will discuss other overarching observations of the data.

Owner Demand for HPB Certification

This section focuses on the impact in the design process and HPB project outcomes when an owner's demand is the sole driver for certification, in contrast to when state, local, and organization mandates are also part of the HPB certification drivers.

Question 9 queried respondents about owner demand for an HPB (Table 13). Respondents could select one of three responses (not owner driven, partially owner driven, or fully owner driven). No respondents reported having a project where the owner did not demand the HPB certification. Ten projects reported the HPB certification was entirely driven by the owner, and nine projects reported that while the HPB certification was partially driven by the owner, it was also driven by state, local, or organizational mandates.

Figure 14 illustrates projects where the HPB certification was entirely driven by the owner were the only projects that utilized C2C certificates and EPDs. All projects that utilized environmental product information accessed recycled content, and nearly all accessed VOC content, regional content, and certified wood. This demonstrates that different, and more, sources of environmental product information were accessed by the projects that the HPB certification was entirely driven by the owner. This confirms the hypothesis that an owner driven HPB certification leads to a different design process than one where the process is also influenced by state, local, or organizational mandates.

The number professionals with HPB training on the teams were 60% for a project whose certification was entirely driven by the owner, and 55% for a project whose certification was also driven by mandates (Table 16). This relatively small difference does not suggest project with the HPB certification being driven by the owner will definitively have more, or less, team members with HPB training (an element of the design approach).

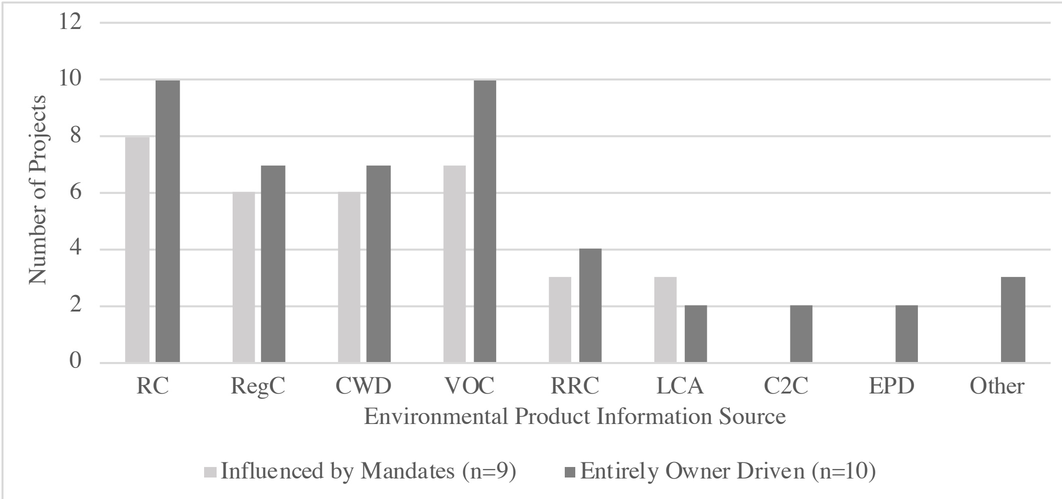


Figure 14. The impact of have the HPB certification driven by the owner on the environmental product information sources reported to be used by projects (design approach)

Table 16. The impact of having the HPB certification driven by the owner on the percentage of the design teams with specific HPB training (design approach)

Influenced by Mandates	55%
Entirely Owner Driven	60%

The large majority of projects with state, local, or organizational mandates for HPB certification achieved LEED Silver (Figure 15), while projects whose certification was entirely driven by the owner are more dispersed across the levels of certification. The project certification outcomes suggest projects with mandates are generally required to reach LEED Silver certification, which corresponds to mandates that can be discerned from the case study projects reported on. Owners who have, or have had, LEED Silver certification mandates for their building projects and are reported in the case studies are the Department of Defense (Energy Independence and Security Act (EISA), 2007), the states of Virginia and Maryland (General Assembly of Virginia, 2012; Maryland Green Building Council, 2017), and several universities. The LEED Gold certified case study project, which had a LEED Silver certification mandate, is a high profile elementary school renovation in a city that has set a high priority on the attributes of HPBs in their communities. The LEED Platinum project had a LEED silver certification mandate, but originally had a LEED Gold goal set by the owner and the design team. The respondent explained that the entire design build team committed to reaching the LEED Gold goal, and that this commitment to sustainability was cited as the contributing factor to a successful LEED Platinum Certification.

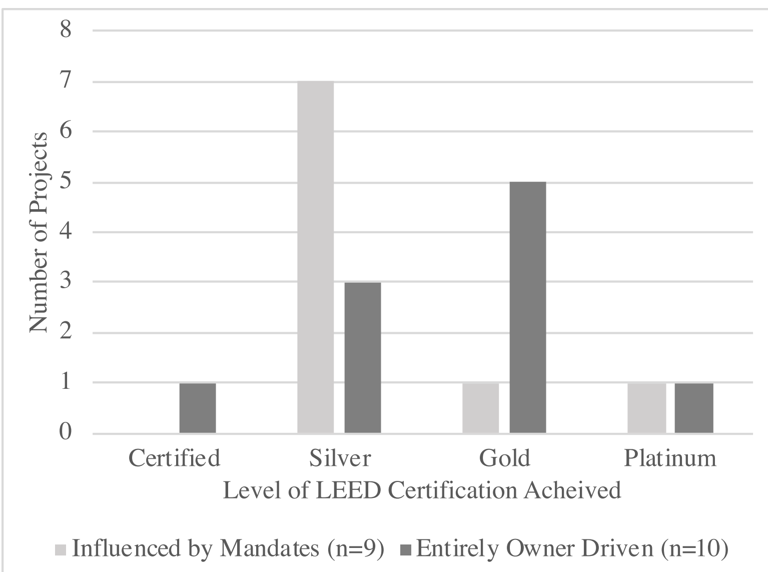


Figure 15. The impact of having the HPB certification driven by the owner on the reported levels of LEED certification achieved (project outcome)

It is likely that owner engagement contributes to the higher levels of certification, and also contributes to the use of different environmental product information. Many of the owners of projects with higher levels of certification are university building environmental centers, or organizations that have environmental issues central to their mission. This seems reasonable, as universities both own and operate most of their buildings. Thus, they are incentivized to spend capital during construction that contributes to lower operating expenses, and can showcase their commitment to sustainability. Essentially, they are owners that are able to take a total cost of ownership perspective, which may motivate the inclusion of more sustainability features that require more initial investment but pay for themselves or contribute to cost savings over the lifetime of the building. Similarly, organizations that focus on environmental issues may see a clear business case for investing in sustainability, as these investments may pay for themselves over time in energy savings, can promote their public image or brand recognition, or some combination thereof.

Consultant on Team

Survey question 14 (Table 13) asked respondents whether there was a consultant engaged in the project by 35% design completion. Twelve projects reported having a consultant engaged by 35% design completion, and seven reported not having a consultant. No projects reported having a consultant engaged later in the design process (i.e., after 35% design complete).

Figure 16 illustrates the impact of a design consultant on the design approach, in terms of the sources of environmental product information. Regional content is used statistically less by the teams with a consultant ($p<0.05$), and to a lesser degree "other" environmental information sources are shown to be used statistically more by the teams with a consultant ($p<0.10$). Note C2C certifications and EPDs are only used by a design team that has engaged a consultant in the process, while all the other environmental information sources are used in both cases. The "Other" environmental information sources reported (Figure 16) were "Health Product Declarations" (reported by two respondents) and "Solar Reflective Index". Given that a consultant focuses on HPB, it stands to reason that they are more experienced with the newer environmental information sources, and this may explain why only teams with consultants queried "newer" sources of environmental product information. The finding that only teams with consultants used C2C and EPD may also be explained by the fact that these information sources are a credit option in LEED v4. So, if a team was seeking to achieve LEED v4 certification, they may have engaged a consultant as the design team was unfamiliar with this newer version of LEED, and by extension, the sources of environmental product information discussed therein.

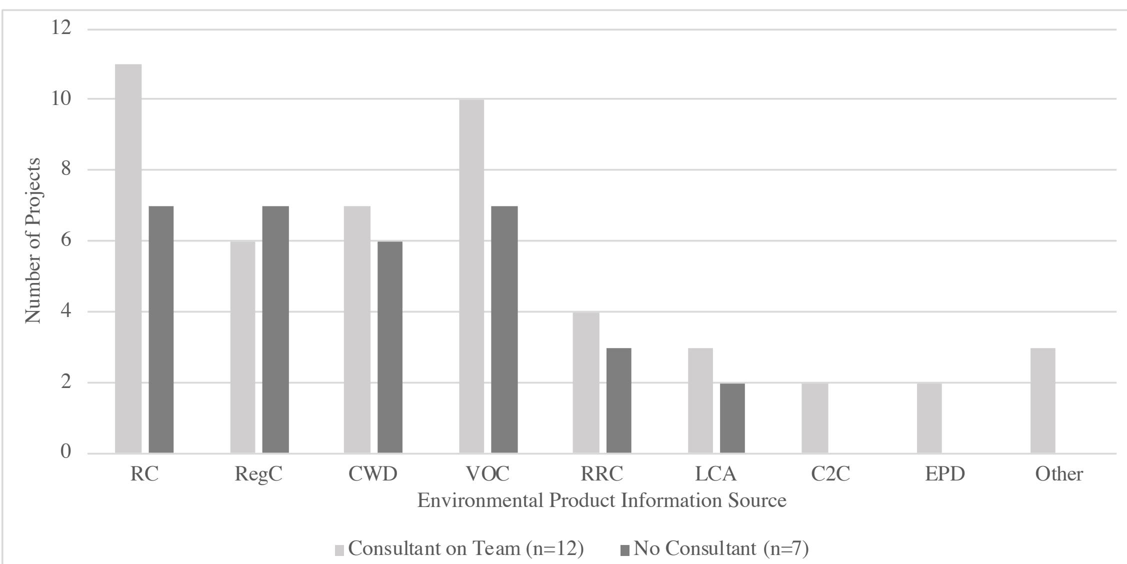


Figure 16. The impact of having a consultant on the design team on the environmental product information sources reported to be used (design approach)

Figure 16 illustrates that different, and more, sources of environmental product information were accessed by the projects that had a consultant engaged on their design team. This confirms the hypothesis that having a consultant leads to a different design process.

The number professionals with HPB training on the teams were 61% for a project with a consultant, and 51% for a project who did not (Table 17). At first pass, it may seem that a design team that includes a larger percentage of personnel trained in HPB certification would be less likely to hire a consultant, as the team would already have the expertise required to complete the project. However, having a design team with more training may actually make them more familiar with the "known unknowns", leading to the hiring of a consultant to handle those "known unknown" aspects of the LEED Certification process. It may also be that a team with HPB-trained members will leverage those trained members to contribute to the certifications process, but the trained team members want to have a consultant manage the process. Additionally, it may be that a HPB trained team will want to hire a consultant to provide a third-party perspective and advocate for sustainable strategies that a designer already engaged in the process may have a hard time doing in addition to completing their responsibilities to the client as an architect, engineer, or contractor.

Table 17. The impact of having a consultant on the design team on the percentage of the design team with specific HPB training (design approach)

Consultant on team	61%
No consultant	51%

Figure 17 illustrates the impact of a consultant on the project outcome. It does not appear that engaging a consultant ensures a higher level of certification. However, Figure 17 suggests that if a project has a mandate to reach LEED silver certification, that design team may be likely to hire a consultant to ensure they achieve the mandated level of certification. This may demonstrate a design team's focus on the Iron Triangle i.e., (time vs cost vs quality); given that the team has a "quality" requirement, i.e., a mandate for HPB certification, they may try to outsource this requirement to a consultant. Likewise, the consultant then has their own Iron Triangle for HPB certification. The consultant is required to analyze the costs compared to the benefits of sustainable strategies and the associated LEED credits, and use that information to help the project include only those measures necessary to reach the mandated certification level as cost-effectively as is practical.

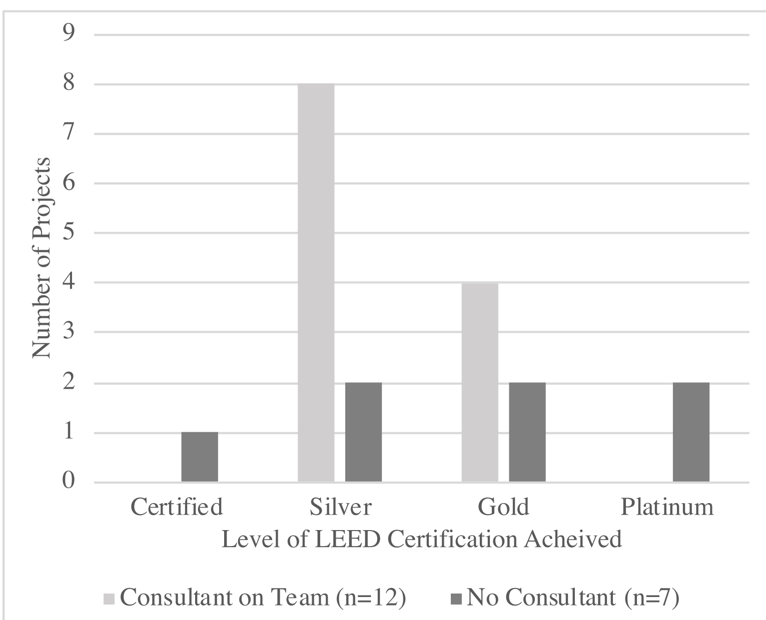


Figure 17. The impact of having a consultant on the design team on the level of LEED certification achieved (project outcome)

Teams that did not employ a consultant delivered the two LEED Platinum projects included in this study. Both teams reported working with the contractor early in the design process, one through design-build project delivery, and the other through construction manager at risk. This early collaboration was cited as key to achieving LEED Platinum certification, as the collaboration allowed the team to develop cost-effective sustainability measures during design that supported a LEED Platinum certification.

Figure 17 illustrates that having a consultant on the design teams does not ensure a higher level of LEED certification, and in turn does not confirm the hypothesis that engaging a consultant in the design process will lead to higher LEED Certification levels (project outcome).

Accessing Information Early

Determination of whether environmental product information for building materials was reviewed early in the design process was determined from question 15 (Table 13). "0-10% (pre-design)" and "10-35% (design development)" were considered to be early in the design process. Thirteen projects reported reviewing environmental information early in the design process, while six reported reviewing the information later than 35% design completion (Figure 18). LCA and other environmental information sources are shown to be used statistically more by the teams that access the information early, with a lower confidence level ($p<0.15$). LCA, C2C certificates, and EPDs were all only accessed early in the design process, suggesting that the teams accessing information earlier are more likely to have greater familiarity with newer sources of information. These results are similar to the impact of having an owner driven HPB certification, and having a consultant engaged in the design process, and is discussed further in Overarching Findings .

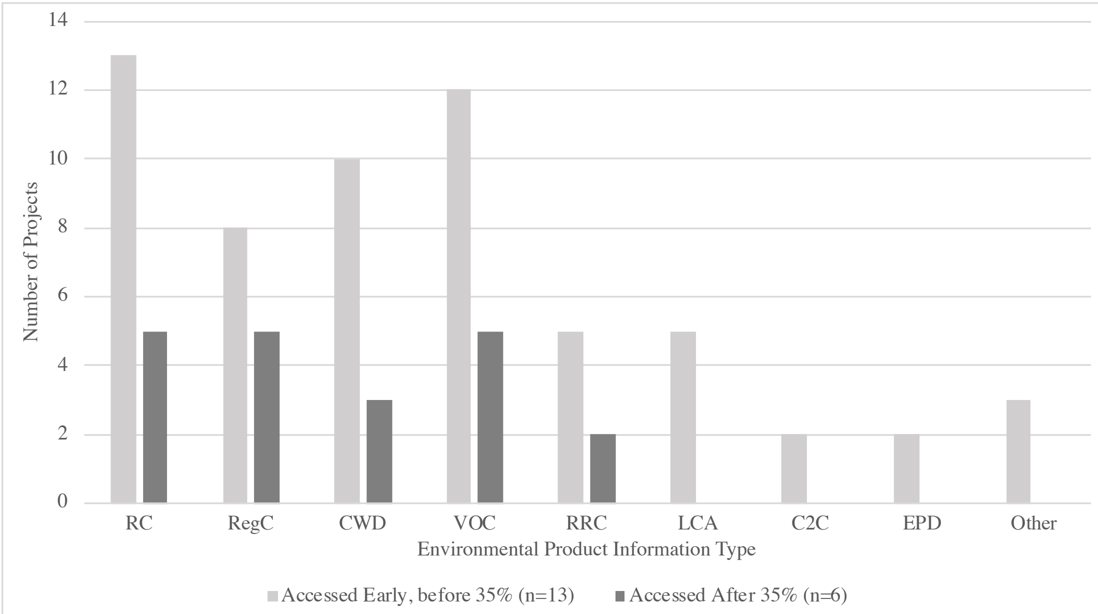


Figure 18. The impact of accessing information early on the environmental product information source used (design approach)

A closer look at the projects that accessed environmental product information later in the design process shows that three of these projects are mandated to be silver certified, and all reported using the same information sources; Recycled Material Content, Regional Material Content, Certified Wood Declarations, and VOC Content. This trend is replicated in the projects that are mandated to be LEED Silver certified, and may be explained by a designer's tendency to use their last successful project as a template for their next project. Recycled Material Content, Regional Material Content, Certified Wood Declarations, and VOC Content are all sources of environmental product information that met requirements for LEED points in its first public rating system, released in 2000 (Building Design & Construction, 2003).

Figure 18 illustrates that different, and more, sources of environmental product information were accessed by the projects that accessed the information early in the design process. This confirms the hypothesis that reviewing environmental product information early leads to a different design process.

Fifty-six percent of the members on teams that reviewed environmental product information early in the design process had HPB training (Table 18). By contrast, sixty-two percent of the members of teams that reviewed the information later in the project had HPB certification. This relatively small difference is inconclusive about the impact of accessing information early on the team composition (an element of the design approach).

Table 18. The impact of accessing environmental product information early in the design process on the percentage of the design team with specific HPB training (design approach)

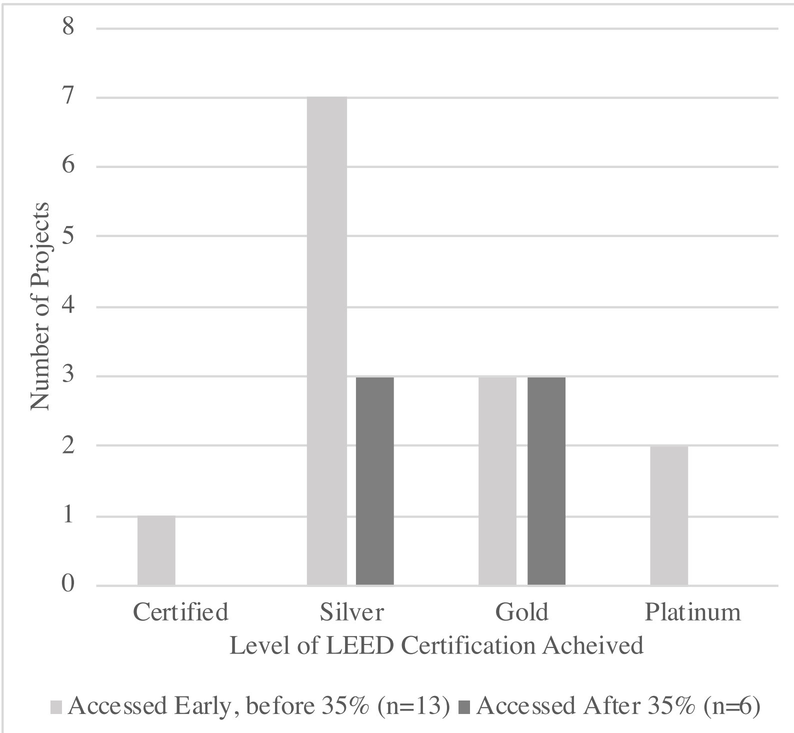
Accessed early, before 35%	56%
Accessed after 35%	62%

This result seems counterintuitive. However, a couple possible explanations can be suggested for this result. The first explanation may be that on a design team with many designers trained in HPB, no one trained person is assigned responsibility for review of the environmental product information, thus this first review ends up falling to later in the project when the team realizes they will require this information. Additionally, teams comprising a larger percentage of HPB-trained staff presumably have previous experience with HPBs; thus, there may already be established rules of thumb, or project standards that allow environmental product information to be accessed later in the design process, and still lead to a successfully certified project. This further corroborates the discussion of the results about Figure 18 (above), confirming the teams who access information later have also not reviewed any of the newer environmental product information available, relying on previous projects or templates for the environmental product information used.

Figure 19 illustrates the impact of accessing environmental product information early on the project outcome (i.e., the level of LEED certification achieved). All of the silver-certified projects that accessed environmental product information later than 35% design complete included a consultant and had mandates for certification. This further strengthens the proposed theory that a project with a mandated certification level will hire a consultant to ensure that requirement is met. Five of the six projects that accessed the information later believed reviewing the environmental product information changed the building material selected, or had a strong influence on the materials selected, while one project was not sure if reviewing the information influenced the building material selection. The research suggests the teams will have a more effective design process (i.e., less redesign) if the environmental product information is reviewed earlier, and is also reflected in earlier survey results (Burke et al., 2018).

Figure 19 illustrates that for each level of certification, the number of projects that access environmental product information prior to 35% design complete is greater than or

Figure 19. The impact of accessing environmental product information early in the design process on the completed level of LEED certification (project outcome)



equal to the number of projects that access this information later. This confirms the hypothesis that reviewing environmental product information early leads to better project outcomes, i.e. higher levels of certification.

Overarching Findings

This section will look at the cases study data collected for underlying trends beyond the three hypotheses tested, and then will look at the design approaches that led to the different project outcomes.

Nearly all projects (18 of 19) reported using environmental information sources about recycled content and VOC content, and a large majority (13 of 19) reported using regional content and certified wood declaration. All of these information sources have been LEED credit documentation options since the first public version of LEED was available in 2000 (Building Design & Construction, 2003). This demonstrates the market penetration of these information sources and supports USGBC's stated goal of market transformation, at least for building materials that use these information sources. This is also quite likely a reason the USGBC concentrated a large portion of the updates in LEED v4 on building materials, by including credits that utilize new information sources, such as LCA, C2C, and EPDs. These new information sources have the potential to again change the way we think about the sustainability of building materials, from examining a single environmental attribute of a product, to looking at the lifecycle of a building material.

Projects that have owner demand for HPB certification, a consultant that specializes in HPB, or are reviewing environmental information early in the design, all have characteristics of teams with significant investment in the LEED certification process. Indeed, data shows that project teams with all three of these conditions present access the newer information sources from the newest version of LEED; this aligns with the commitment to sustainability evidenced by having owner commitment, an HPB consultant, and a process that queries environmental product information early on.

The hypotheses did not prove that the design teams' HPB training is affected by any of the independent variables. However, it should be noted that every design team reported having at least one LEED AP + Specialty, and at least one LEED AP, with the average design team reporting two of each of them. Additionally, 13 of the design teams reported having a team member with energy modeling training. This further demonstrates the market influence USGBC's LEED has had on the AEC industry. In July 2016, there were over 175,000 LEED credential holders in the US, with 107,00 LEED APs, and 37,000 LEED AP + Specialty (Tufts, 2016).

Fourteen of the 18 respondents believed reviewing environmental product information had an impact on the material selections, either as a primary contribution to the reason certain materials were selected or in changing the material selected. This supports the findings discussed in Accessing Information Early, describing the criticality of examining this information to allow it to inform the design. In turn, this leads to less frequent re-design, and thus, a more successful design process.

The certification of the one LEED Certified case study project was entirely driven by the client, and was noted to be the first for the city who owned it. Additionally, the city committed to LEED Silver certification on all city owned buildings in the future.

LEED Silver certification is the most common certification level required by state, local, and organizational mandates, and is reflected in the large proportion (seven of ten) of silver projects that were partially driven by mandates. For LEED Silver projects that have a mandate for certification the majority (five of seven) had a consultant on their team, showing this is quite likely an impetus for projects to hire a consultant. In addition, for projects that had a certification mandate and included a consultant on the design team (n=7), the majority reviewed environmental information early in the design, prior to 35%. This aligns with comments expressed throughout the research about the importance of engaging the entire team, including the consultant, as early as possible in the design process.

All of the LEED Gold certified projects have owners with a strong commitment to sustainability in their mission, either as environmental centers for universities, or organizations with a central focus on the environment. Indeed, five of the six Gold certified projects reported the owner being the primary driver for their HPB certification.

Both of the LEED Platinum certified buildings utilized environmental product information early in the design and did not have a consultant on the team. This reinforces early review of environmental information is an important consideration for projects pursuing the highest level of LEED certification. It also illustrates that a consultant is no required to achieve sustainability outcomes, but expertise in HPB projects is required.

Conclusion

The survey in this chapter was created and administered based on results from focus groups (chapter 3) and an earlier survey (chapter 2) that suggested that owner commitment to an HPB certification, education of the design team members, and early access of environmental product information would be most impactful on both the sources and use of environmental product information (i.e., the "design approach") as well as the level of certification a project eventually receives (i.e., the "outcome"). This work illustrated that owner demand for an HPB, design team training, and early access to environmental information do, in fact, impact the product information sources accessed. However, none of these variables seems to impact the makeup of the team, in terms of the number of HPB trained staff on the team. This study further suggests that owner demand for an HPB certification and accessing the environmental product information early impact the project outcome while engaging a consultant on the project does not. This reveals an opportunity for future work that explores the impact of a team's HPB training on the design approach and outcome. Future work may also include deploying this survey to a larger audience to facilitate statistical analysis of results. Future researchers may also opt to dive deeper into this analysis, and follow a similar case-based approach but use interviews or other research methods to elicit clearer understanding of how state, local, and organizational mandates for LEED certification and newer sources of environmental information really impact the full design process, rather than focusing exclusively on the early design decision making processes related to construction materials.

The main limitation of the study is that the results are based on a sample of 19 case study projects collected from AEC practitioners. Since this is a relatively small convenient sample, that does not allow for robust checking of statistical significance, the numbers presented herein should not be assumed to be representative of the whole AEC industry. However, the case study projects provide a rich and diverse set of experiences to help understand the influences of several strategies for HPB projects that utilize environmental product information.

CHAPTER 5 – SUMMARY

Chapter 5 summarizes the main findings of chapters, 2, 3, and 4 in terms of the research questions, and then presents suggestions for future work.

Conclusions

Chapter 2 answered the research question: What are the strategies being used in the AEC industry to inform design and construction decisions for construction material in high performance buildings? There is a small portion of AEC firms that have a policy for evaluating the use of environmental product information sources. Despite this, all disciplines (i.e., architect, engineer, interior designer, and contractor) have typically used at least one source of information, with architects being the most likely to access all sources, and the access is typically driven by their engagement in an HPB project that requires a LEED certification. Likewise, the use of EPDs are being driven by LEED v4, and users believe their standardized format is valuable to their design, and to help educate their team members and the building owners. Further, those most familiar with EPDs think it is important to use them early in the design to be able to inform their design decisions.

Chapter 3 utilized a systems engineering tool to document answers to the research question: What actions in the design process can an AEC team take to most effectively utilize emerging environmental information for construction materials to inform design for higher performing buildings? Using design teams as focus groups to collect MSCs in order explore a modification to the design process, proved to be effective for this specific situation. The author was able to thoroughly explore the AEC practitioners' suggested strategies for incorporating EPDs into their conceptual design for a number of owner types and project delivery types. Extensive coding of the MSC and associated focus group transcripts resulted in five distinct design process modifications; engage an additional stakeholder, additional iterations, owner engagement, visibility of the project, and HPB mandate.

Chapter 4 used 19 HPB project case studies to answer the research question: What project characteristics have an impact on the HPB design team's design approach and the project's certification outcome? The results from the focus groups and the previously described survey suggested that owner commitment to an HPB certification, education of the design team members, and early access of environmental product information would be most impactful on both the sources and use of environmental product information (i.e., the "design approach") as well as the level of certification a project eventually receives (i.e., the "outcome"). This work illustrated that owner demand for an HPB, design team training, and early access to environmental information do, in fact, impact the product information sources accessed. This study further suggested that owner demand for an HPB certification and accessing the environmental product information early impact the project outcome while engaging a consultant on the project does not.

Future Work

The majority of this research focused on design teams that have experience in HPB projects, so there is an opportunity for future work to look a design teams with different exposure to HPB certification. This research may uncover different opportunities for effective use of new sources of environmental product information, or may further strengthen the findings within this work.

There is an opportunity to dive deeper into this analysis, and follow similar methods but use interviews or other research methods to elicit clearer understanding of how newer sources of environmental information really impact the full design process, rather than focusing exclusively on the early design decision making processes related to construction materials. Additionally, all phases of the research may be deployed to a larger audience to facilitate further convergence of findings, generalizability, and additional statistical analysis of results.

REFERENCES

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renewable and Sustainable Energy Reviews, 67*, 408-416. doi:10.1016/j.rser.2016.09.058

Asmar, M. E., Hanna, A. S., & Loh, W.-Y. (2013). Quantifying Performance for the Integrated Project Delivery System as Compared to Established Delivery Systems. *Journal of Construction Engineering and Management, 139*(11). doi:doi:10.1061/(ASCE)CO.1943-7862.0000744

Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering, 11*(3), 241-252. doi:doi:10.1061/(ASCE)LM.1943-5630.0000127

Bakhoum, E. S., & Brown, D. C. (2012). Developed Sustainable Scoring System for Structural Materials Evaluation. *Journal of Construction Engineering and Management, 138*(1), 110-119. doi:doi:10.1061/(ASCE)CO.1943-7862.0000412

Baumann, H., & Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA: An orientation in life cycle assessment methodology and application*. Poland: Studentlitteratur.

Buckley, B., & Logan, K. (2016). World green building trends 2016: developing markets accelerate global green growth. *Bedford (MA): Dodge Data & Analytics*.

Building Design & Construction. (2003). White Paper on Sustainability. *Building Design & Construction*.

Burke, R. D., Parrish, K., & Asmar, M. E. (2018). Environmental Product Declarations: Use in the Architectural and Engineering Design Process to Support Sustainable Construction. *Journal of Construction Engineering and Management, 144*(5), 04018026. doi:doi:10.1061/(ASCE)CO.1943-7862.0001481

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews, 29*, 394-416. doi:http://dx.doi.org/10.1016/j.rser.2013.08.037

Chick, A., & Micklethwaite, P. (2004). Specifying recycled: understanding UK architects' and designers' practices and experience. *Design Studies, 25*(3), 251-273. doi:http://dx.doi.org/10.1016/j.destud.2003.10.009

Cradle to Cradle Products Innovation Institute. (2017a). Cradle to Cradle Certified Products Registry. Retrieved from http://www.c2ccertified.org/products/registry

Cradle to Cradle Products Innovation Institute. (2017b). Get Cradle to Cradle Certified. Retrieved from http://www.c2ccertified.org/get-certified/product-certification

Damelio, R. (2011). Chapter 5. Cross-Functional Process Map (aka Swimlane Diagram) *The basics of process mapping* (pp. 73-92).

Design-Build Institute of America. (2018). What is Design-Build? Retrieved from https://www.dbia.org/about/Pages/What-is-Design-Build.aspx

Eckert, C. M., & Clarkson, P. J. (2010). Planning development processes for complex products. *Research in Engineering Design, 21*(3), 153-171. doi:10.1007/s00163-009-0079-0

Eisenbart, B., Gericke, K., & Blessing, L. (2011). *A Framework for Comparing Design Modelling Approaches Across Discpilines.* Paper presented at the 18th International Conference on Engineering Design (ICED 11), Lyngby/Copenhagen, Denmark.

Public Law 110-140, Public Law 110-140 C.F.R. (2007).

EPD International AB. (2017). EPD, The Green Yardstick. Retrieved from http://www.environdec.com/

Gelowitz, M. D. C., & McArthur, J. J. (2016). *Investigating the effect of environmental product declaration adoption in LEED on the construction industry: A case study*. Paper presented at the International Conference on Sustainable Design, Engineering and Construction, Tempe, AZ.

Virginia High Performance Buildings Act, 8 C.F.R. § 2.2-1182, 2.2-1183 (2012).

Gibson, G. E., & Hamilton, M. R. (1994). *Analysis of pre-project planning effort and success variables for capital facility projects*: The Construction Industry Institute.

Gibson, G. E., Kaczmarowski, J. H., & Lore, H. E. (1995). Preproject-Planning Process for Capital Facilities. *Journal of Construction Engineering and Management, 121*(3), 312-318. doi:doi:10.1061/(ASCE)0733-9364(1995)121:3(312)

Gibson, G. E., & Whittington, D. A. (2010). Charrettes as a Method for Engaging Industry in Best Practices Research. *Journal of Construction Engineering and Management, 136*(1), 66-75. doi:doi:10.1061/(ASCE)CO.1943-7862.0000079

Green Building Initiative. (2016a). Green Globes for New Construction, Technical Reference Manual, Version 1.45 *Materials and Resources* (pp. 138-206).

Green Building Initiative. (2016b). Materials and Resources *Green Globes for New Construction, Technical Reference Manual, Version 1.45* (pp. 138-206).

Green Building Initiative. (2017). Certified Building Directory. Retrieved from https://www.thegbi.org/project-portfolio/certified-building-directory/

Hale, D. R., Shrestha, P. P., Gibson, G. E., & Migliaccio, G. C. (2009). Empirical Comparison of Design/Build and Design/Bid/Build Project Delivery Methods. *Journal of Construction Engineering and Management, 135*(7), 579-587. doi:doi:10.1061/(ASCE)CO.1943-7862.0000017

Hofstetter, P., & Mettier, T. M. (2003). What Users Want and May Need: Insights from a Survey of Users of a Life-Cycle Tool. *Journal of Industrial Ecology, 7*(2), 79-101. doi:10.1162/108819803322564361

Holloway, S., & Parrish, K. (2015). The contractor's role in the sustainable construction industry. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 168*(2), 53-60. doi:10.1680/ensu.14.00026

Javernick-Will, A. (2012). Motivating Knowledge Sharing in Engineering and Construction Organizations: Power of Social Motivations. *Journal of Management in Engineering, 28*(2), 193-202. doi:doi:10.1061/(ASCE)ME.1943-5479.0000076

Kam-Biron, M., & Podesto, L. The Growing Role of Wood in Building Sustainability *AEI 2011*.

Kam-Biron, M., & Podesto, L. (2011). The Growing Role of Wood in Building Sustainability *AEI 2011*.

Kibert, C. J. (2016). *Sustainable construction: green building design and delivery*: John Wiley & Sons.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., . . . Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal Of Exposure Analysis And Environmental Epidemiology, 11*, 231. doi:10.1038/sj.jea.7500165

Klotz, L., Horman, M., & Bodenschatz, M. (2007). A Lean Modeling Protocol for Evaluating Green Project Delivery. *Lean Construction Journal, 3*(1), 1-18.

Kobayashi, H. (2005). Strategic evolution of eco-products: a product life cycle planning methodology. *Research in Engineering Design, 16*(1), 1-16. doi:10.1007/s00163-005-0001-3

Lamé, G., Leroy, Y., & Yannou, B. (2017). Ecodesign tools in the construction sector: Analyzing usage inadequacies with designers' needs. *Journal of Cleaner Production, 148*, 60-72. doi:https://doi.org/10.1016/j.jclepro.2017.01.173

Lapinski, A. R., Horman, M. J., & Riley, D. R. (2006). Lean Processes for Sustainable Project Delivery. *Journal of Construction Engineering and Management, 132*(10), 1083-1091. doi:doi:10.1061/(ASCE)0733-9364(2006)132:10(1083)

Li, Y. Y., Chen, P.-H., Chew, D. A. S., Teo, C. C., & Ding, R. G. (2011). Critical Project Management Factors of AEC Firms for Delivering Green Building Projects in Singapore. *Journal of Construction Engineering and Management, 137*(12), 1153-1163. doi:doi:10.1061/(ASCE)CO.1943-7862.0000370

Macmillan, S., Steele, J., Kirby, P., Spence, R., & Austin, S. (2002). Mapping the design process during the conceptual phase of building projects. *Engineering Construction and Architectural Management, 9*(3), 174-180. doi:10.1046/j.1365-232X.2002.00253.x

Magent, C. S., Korkmaz, S., Klotz, L. E., & Riley, D. R. (2009). A Design Process Evaluation Method for Sustainable Buildings. *Architectural Engineering & Design Management, 5*(1/2), 62-74. doi:10.3763/aedm.2009.0907

House Bill 942, House Bill 942 C.F.R. § 4-809 (2017).

Melão, N., & Pidd, M. (2000). A conceptual framework for understanding business processes and business process modelling. *Information Systems Journal, 10*(2), 105-129. doi:10.1046/j.1365-2575.2000.00075.x

Minchin, R. E., Li, X., Issa, R. R., & Vargas, G. G. (2013). Comparison of Cost and Time Performance of Design-Build and Design-Bid-Build Delivery Systems in Florida. *Journal of Construction Engineering and Management, 139*(10). doi:doi:10.1061/(ASCE)CO.1943-7862.0000746

Mollaoglu-Korkmaz, S., Swarup, L., & Riley, D. (2013). Delivering Sustainable, High-Performance Buildings: Influence of Project Delivery Methods on Integration and Project Outcomes. *Journal of Management in Engineering, 29*(1), 71-78. doi:doi:10.1061/(ASCE)ME.1943-5479.0000114

O'Donovan, B., Eckert, C., Clarkson, J., & Browning, T. R. (2005). Design planning and modelling *Design process improvement* (pp. 60-87): Springer.

OECD. (2015). *Material Resources, Productivity and the Environment*. Retrieved from Paris:

Office of Land and Emergency Management. (2016). *Advancing Sustainable Materials Management: 2014 Fact Sheet*. Retrieved from Washington, DC:

Olinzock, M. A., Landis, A. E., Saunders, C. L., Collinge, W. O., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2015). Life cycle assessment use in the North American building community: summary of findings from a 2011/2012 survey. *The International Journal of Life Cycle Assessment, 20*(3), 318-331. doi:10.1007/s11367-014-0834-y

Park, H., & Cutkosky, M. R. (1999). Framework for Modeling Dependencies in Collaborative Engineering Processes. *Research in Engineering Design, 11*(2), 84-102. doi:10.1007/pl00003885

Parrish, K., & Regnier, C. (2012). Proposed design process for deep energy savings in commercial building retrofit projects. *Journal of Architectural Engineering, 19*(2), 71-80.

Reff, A., Turpin, B. J., Porcja, R. J., Giovennetti, R., Cui, W., Weisel, C. P., . . . Farrar, C. (2005). Functional group characterization of indoor, outdoor, and personal PM2.5: results from RIOPA. *Indoor Air, 15*(1), 53-61. doi:doi:10.1111/j.1600-0668.2004.00323.x

Robichaud, L. B., & Anantatmula, V. S. (2011). Greening Project Management Practices for Sustainable Construction. *Journal of Management in Engineering, 27*(1), 48-57. doi:doi:10.1061/(ASCE)ME.1943-5479.0000030

Rodriguez-Nikl, T., Kelley, J., Xiao, Q., Hammer, K., & Tilt, B. (2015). Structural Engineers and Sustainability: An Opinion Survey. *Journal of Professional Issues in Engineering Education and Practice, 141*(3). doi:doi:10.1061/(ASCE)EI.1943-5541.0000228

Said, H., & Berger, L. (2014). Future Trends of Sustainability Design and Analysis in Construction Industry and Academia. *Practice Periodical on Structural Design and Construction, 19*(1), 77-88. doi:doi:10.1061/(ASCE)SC.1943-5576.0000181

Saunders, C. L., Landis, A.E., Mecca, L., Jones, A.K., Schaefer, L.A., Bilec, M.M. (2013). Analyzing the Practice of Life Cycle Assessment: Focus on the Building Sector. *Journal of Industrial Ecology, 17*(5), 777-788. doi: DOI: 10.1111/jiec.12028

Schaufelberger, J., & Cloud, J. (2009). LEED Certification: A Constructor's Perspective *Building a Sustainable Future*.

Sheskin, D. J. (2007). *Handbook of Parametric and Nonparametric Statistical Procedures*: Chapman & Hall/CRC.

Smith, R. P., & Morrow, J. A. (1999). Product development process modeling. *Design Studies, 20*(3), 237-261. doi:https://doi.org/10.1016/S0142-694X(98)00018-0

Tufts, R. (2016). LEED Professionals at a glance: July 2016.   Retrieved from https://www.usgbc.org/articles/leed-professionals-glance-july-2016

U.S. Environmental Protection Agency. (2007). *Municipal Solid Waste in United States: 2007 Facts and Figures*.

U.S. Green Building Council. (2009). LEED Reference Guide for Green Building Design and Construction *Material and Resources*. Washington, D.C.: U.S. Green Building Council.

U.S. Green Building Council. (2013). LEED Reference Guide for Building Design and Construction. Washington, DC: U.S. Green Building Council.

U.S. Green Building Council. (2017, 25 January 2017). Infographic: Top 10 state for LEED in 2016. Retrieved from https://www.usgbc.org/articles/infographic-top-10-states-for-leed-in-2016

van der Aalst, W. (2000). Loosely coupled interorganizational workflows. *Information & Management, 37*(2), 67-75. doi:http://dx.doi.org/10.1016/S0378-7206(99)00038-5

Wynn, D. C., & Clarkson, P. J. (2017). Process models in design and development. *Research in Engineering Design*. doi:10.1007/s00163-017-0262-7

Wynn, D. C., & Eckert, C. M. (2017). Perspectives on iteration in design and development. *Research in Engineering Design, 28*(2), 153-184. doi:10.1007/s00163-016-0226-3

Yassine, A., Joglekar, N., Braha, D., Eppinger, S., & Whitney, D. (2003). Information hiding in product development: the design churn effect. *Research in Engineering Design, 14*(3), 145-161. doi:10.1007/s00163-003-0036-2

Yin, R. K. (2014). *Case study research: Design and methods* (Fifth ed.): Sage publications.

Zanni, M.-A., Soetanto, R., & Ruikar, K. (2014). Defining the sustainable building design process: methods for BIM execution planning in the UK. *International Journal of Energy Sector Management, 8*(4), 562-587. doi:doi:10.1108/IJESM-04-2014-0005

Zhang, X., Hao, Y., & Thomson, V. (2015). Taking Ideas from Paper to Practice: A Case Study of Improving Design Processes through Detailed Modeling and Systematic Analysis. *IFAC-PapersOnLine, 48*(3), 1043-1048. doi:https://doi.org/10.1016/j.ifacol.2015.06.221

Zhong, Y., Ling, F. Y. Y., & Wu, P. (2017). Using Multiple Attribute Value Techinique for the Selection of Structural Frame Material to Acheive Sustainability and Constructability. *Journal of Construction Engineering and Management, 143*(2). doi:https://doi.org/10.1061/(ASCE)CO.1943-7862.0001210

Zimina, D., Ballard, G., & Pasquire, C. (2012). Target value design: using collaboration and a lean approach to reduce construction cost. *Construction Management and Economics, 30*(5), 383-398. doi:10.1080/01446193.2012.676658

APPENDIX A

CO-AUTHOR PERMISSION FOR USE OF JOURNAL ARTICLE

CHAPTER 2 – ENVIRONMENTAL PRODUCT DECLARATIONS: USE IN THE ARCHITECTURAL AND ENGINEERING DESIGN PROCESS TO SUPPORT SUSTAINABLE CONSTRUCTION was written in collaboration with Drs. Kristen Parrish and Mounir El Asmar, who have granted their permission for use in the dissertation.

APPENDIX B

ARIZONA STATE UNIVERSITY HUMAN SUBJECTS INSITUTIONAL REVIEW BOARD APPROVAL DOCUMENTS

Knowledge Enterprise Development
ARIZONA STATE UNIVERSITY

SOCIAL BEHAVIORAL INSTRUCTIONS AND TEMPLATE		
NUMBER	DATE	PAGE
HRP-503a	3/28/2018	1 of 4

Instructions and Notes:

- Depending on the nature of what you are doing, some sections may not be applicable to your research. If so, mark as "NA".
- When you write a protocol, keep an electronic copy. You will need a copy if it is necessary to make changes.

1 Protocol Title

Examining the Influence of Early Design Decisions on Material Impacts in High Performing Buildings

2 Background and Objectives

Provide the scientific or scholarly background for, rationale for, and significance of the research based on the existing literature and how will it add to existing knowledge.

- Describe the purpose of the study.
- Describe any relevant preliminary data or case studies.
- Describe any past studies that are in conjunction to this study.

The purpose of this research project is to gather information on the policies, procedures and impact of early design decisions on the environmental impact, or ability to affect the environmental impact, of building materials in commercial building projects. Architecture and Engineering (AE) professionals follow a dynamic, yet highly practiced, process to make early design decisions based upon limited client desires and restrictions.

Academic literature has provided significant design process analysis, as well as exploration of the use of environmental building product information in high performing buildings. However, current expansion of the development and use of environmental building product data requires an examination of the design process to affect the overall environmental impact of buildings utilizing the new material information.

3 Data Use

Describe how the data will be used. Examples include:

- Dissertation, Thesis, Undergraduate honors project
- Publication/journal article, conferences/presentations
- Results released to agency or organization
- Results released to participants/parents
- Results released to employer or school
- Other (describe)

We will present our methods and findings at an annual conference in journal articles, as well as disseminating the results and conclusions to industry participants and partners.

The preliminary research outcomes will be included in a proposal defense, and the final outcomes will be included in Rebekah Burke's final dissertation. Ms. Burke has completed CITI training.

4 Inclusion and Exclusion Criteria

Describe the criteria that define who will be included or excluded in your final study sample. If you are conducting data analysis only describe what is included in the dataset you propose to use.

Indicate specifically whether you will target or exclude each of the following special populations:

- Minors (individuals who are under the age of 18)
- Adults who are unable to consent
- Pregnant women
- Prisoners
- Native Americans
- Undocumented individuals

The participants will be experienced architecture and engineering professionals.

All minors, adults who are unable to consent, prisoners and undocumented individual will be excluded from the final study sample.

5 Number of Participants

Indicate the total number of participants to be recruited and enrolled*:* 500 for survey, 50 for focus group

6 Recruitment Methods

- Describe who will be doing the recruitment of participants.
- Describe when, where, and how potential participants will be identified and recruited.
- Describe and attach materials that will be used to recruit participants (attach documents or recruitment script with the application).

A current ASU PhD student (Rebekah Burke) will email two local USGBC chapter contacts and known industry contacts with the intention to distribute the online survey to AE professionals.

A current ASU PhD student (Rebekah Burke) will contact industry contacts with the intention to recruit participants for a focus group. There will be a total of 3 focus groups. Recruitment tools have been attached.

7 Procedures Involved

Describe all research procedures being performed, who will facilitate the procedures, and when they will be performed. Describe procedures including:

- The duration of time participants will spend in each research activity.
- The period or span of time for the collection of data, and any long term follow up.
- Surveys or questionnaires that will be administered (Attach all surveys, interview questions, scripts, data collection forms, and instructions for participants to the online application).
- Interventions and sessions (Attach supplemental materials to the online application).
- Lab procedures and tests and related instructions to participants.
- Video or audio recordings of participants.
- Previously collected data sets that that will be analyzed and identify the data source (Attach data use agreement(s) to the online application).

This research will take place during the summer and fall of 2016. Initial survey questions were developed from preliminary research, study and work experience from the PhD student and associated committee. Additional (ongoing) communication with AE professionals and feedback from the industry will be incorporated into the study.

The Qualtrics data software, available through ASU affiliation, is utilized as an online survey distribution and data collection and storage. The survey link will be distrubuted via email to industry contacts and the mailing list of 2 local USGBC chapters.

Partiicpants are anticipated to spend 15 minutes answering questions about policies, procedures and impact of early design decisions on the environmental impact, or ability to affect the environmental impact, of building materials in commercial building projects.

A copy of the survey questions are included as an attachment to this research protocol.

Focus group protocol has been developed from preliminary research, study and work experience from the PhD student and associated committee members. Adjustments to the focus group protocol and format will be incorporated into the study from participant feedback.

The same qualtrics survey will be administered in a physical form with the focus group participants. The pdf/hard copy form will be provided to the participants to bring to the focus group completed, and will serve as their consent to participate. The completed consent form will be collected from each participant. The surveys completed by the focus group participants will not be linked to their focus conversation.

A script will not be used for the focus group, but the background information, and presentation to be given has been attached.
The focus group participants will complete 2 message sequence charts as part of the focus group, documenting the early design decisions in their design process (the colored sheets, the forms are attached).

The participants in the focus groups will be notified of the sessions being video recorded.

8 Compensation or Credit

- Describe the amount and timing of any compensation or credit to participants.
- Identify the source of the funds to compensate participants
- Justify that the amount given to participants is reasonable.
- If participants are receiving course credit for participating in research, alternative assignments need to be put in place to avoid coercion.

No compensation will be offered to the participants.

9 Risk to Participants
List the reasonably foreseeable risks, discomforts, or inconveniences related to participation in the research. Consider physical, psychological, social, legal, and economic risks.

There are no risks anticipated as a result of this research survey and study. The participation is voluntary, and the responses and analysis will not be associated with the respondent's names.

10 Potential Benefits to Participants
Realistically describe the potential benefits that individual participants may experience from taking part in the research. Indicate if there is no direct benefit. Do **not** include benefits to society or others.

The questions will solicit information about the respondents actions related to the policies, procedures and impact of early design decisions on the environmental impact, or ability to affect the environmental impact, of building materials in commercial building projects

11 Privacy and Confidentiality
Describe the steps that will be taken to protect subjects' privacy interests. "Privacy interest" refers to a person's desire to place limits on with whom they interact or to whom they provide personal information. Click here for additional guidance on ASU Data Storage Guidelines.

Describe the following measures to ensure the confidentiality of data:
- Who will have access to the data?
- Where and how data will be stored (e.g. ASU secure server, ASU cloud storage, filing cabinets, etc.)?
- How long the data will be stored?
- Describe the steps that will be taken to secure the data during storage, use, and transmission. (e.g., training, authorization of access, password protection, encryption, physical controls, certificates of confidentiality, and separation of identifiers and data, etc.).
- If applicable, how will audio or video recordings will be managed and secured. Add the duration of time these recordings will be kept.
- If applicable, how will the consent, assent, and/or parental permission forms be secured. These forms should separate from the rest of the study data. Add the duration of time these forms will be kept.
- If applicable, describe how data will be linked or tracked (e.g. masterlist, contact list, reproducible participant ID, randomized ID, etc.).

If your study has previously collected data sets, describe who will be responsible for data security and monitoring.

The Qualtrics software is password-protected which secures the raw data collected from the survey. If individuals are interested in the final analysis of data or are open to participate in future project initiatives, they are able to provide their contact information, but is not required. Moreover, de-identified/anonymous and aggregated data (e.g., all responses will be presented together to illustrate a trend) will be used to develop publications, presentations, or reports. If there is a quote that I would like to share, and the respondent voluntarily provided contact information, I will ask their permission before quoting them with attribution in any publication.
The online access for data analysis can be viewed only by the research project lead and associated committee members.
Data storage will follow existing protocols and be stored for 5 years post-collection on ASU's Qualtrics server space.

12 Consent Process
Describe the process and procedures process you will use to obtain consent. Include a description of:
- Who will be responsible for consenting participants?
- Where will the consent process take place?
- How will consent be obtained?
- If participants who do not speak English will be enrolled, describe the process to ensure that the oral and/or written information provided to those participants will be in that language. Indicate the language that will be used by those obtaining consent. Translated consent forms should be submitted after the English is approved.

The PhD student, Rebekah Burke will provide for effective communication and a link to the AE industry professionals interested in providing information about their early design decision process.

See the attached Consent Form to accompany the survey.

This same survey has been modified to include consent for recording for the focus group participation and is attached.

13 Training

Provide the date(s) the members of the research team have completed the CITI training for human participants. This training must be taken within the last 4 years. Additional information can be found at: Training.

Kristen Parrish: 1/21/13
Rebekah Burke 1/13/15

Study Title: Examining the Influence of Early Design Decisions on Material Impacts in High Performing Buildings

My name is Rebekah Burke, I am a PhD student working under the direction of Dr. Kristen Parrish, in the School of Sustainable Engineering and the Built Environment at Arizona State University. I am conducting a research study to examine the policy, procedures and perceived impacts of early design decisions on the environmental impact of building materials in commercial building projects.

I am coordinating focus groups/workshops with AE firms to learn about their design process, particularly as it relates to early design decisions relating to the environmental and health impacts of building materials. I would love to have participation from your firm!

I am asking for the commitment of 6-8 team members, architects, engineers, interior designers and project members, who are currently working together, or have worked on the same team in the past. The team members should have familiarity with writing specifications on high performing buildings. I would host the workshop in your office, with an expected length less than 2-hours. The focus group will be video recorded.

To engage in the focus group I will need each participant to take 15 minute to complete the attached survey to help researchers and the industry understand the challenges and opportunities we are facing in selecting the materials to design healthy and high performing buildings for our clients. **Note you must be 18 or older to participate.**

Providing the completed questionnaire at the beginning of the focus group will be considered consent to participate. Should you have questions of comments about the focus group or the survey, please do not hesitate to contact Rebekah Burke at Rebekah.burke@asu.edu (757-621-0522), or Kristen Parrish at Kristen.Parrish@asu.edu (480-727-6363).

Sincerely,
Rebekah Burke and Dr. Kristen Parrish
School of Sustainable Engineering and the Built Environment
Arizona State University

Ira A. Fulton Schools of Engineering
ARIZONA STATE UNIVERSITY

Dear Attendee:

Thank you for agreeing to participate in the Design Decisions and Building Materials for High Performing and Healthy Buildings focus group workshop on XXX at XX in XX. The primary contact for this workshop is Rebekah Burke, ASU, (757) 621-0522, rebekah.burke@asu.edu.

Several items are attached: agenda, brief overview of the research project, and a background information questionnaire. Please take a few minutes to familiarize yourself with the material prior to the workshop. The background information questionnaire **should be filled out prior to the workshop**, if at all possible, and should take you 10-15 minutes. Completion of the background questionnaire, with signature and date on the final page, will be considered consent. We ask that you have a working knowledge (and preferably been a participant on) at least one high performing building, are familiar with the general design process and any nuances associated with a high performing building design process, as well as the specification writing process. Additionally, you must be a minimum of 18 years of age to participate.

We will use your experience and feedback to examine the building design process, information available for building material design decisions and work towards determining optimal methods for incorporation and utilization of building product data for high performing and healthy buildings. The content of this study is funded by the National Science Foundation Graduate Research Fellowship Program.

All of the information gathered including the focus group responses will be video recorded and will be held in the strictest confidence. However, due to the nature of focus groups, complete confidentiality cannot be guaranteed. Your participation in the focus group is voluntary. You can stop or leave at any time. The focus group will be expected to last less than 2 hours. A full explanation of the focus group process will be provided at the onset of the meeting. If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788.

The focus group is designed to share your experience with us (the researchers), as well as peers. As such, we anticipate that you will benefit from the interaction and contribute to improvement in our industry.

If you have questions regarding the design decisions and building materials for high performing and healthy buildings focus group or this package, please contact me at 757.621.0522, Rebekah.burke@asu.edu, or Kristen Parrish at 480.727.6363, kristen.parrish@asu.edu.

Sincerely,

Rebekah Burke, PE (VA), LEED AP BD+C
National Science Foundation Graduate Research Fellow
School of Sustainable Engineering and the Built Environment
Arizona State University

School of Sustainable Engineering and the Built Environment
PO Box 870204 Tempe, AZ 85287-0204
(480) 965-3589 FAX: (480) 965-1769

Early Design Decision Impact on Building Materials

Thank you for agreeing to participate in the Design Decisions and Building Materials for High Performing and Healthy Buildings focus group workshop on XXX at XX in XX. The primary contact for this workshop is Rebekah Burke, ASU, (757) 621-0522, rebekah.burke@asu.edu.

This background information questionnaire **should be filled out prior to the workshop**, if at all possible, and should take you 10-15 minutes. Completion of the background questionnaire, with signature and date on the final page, will be considered consent. We ask that you have a working knowledge (and preferably been a participant on) at least one high performing building, are familiar with the general design process and any nuances associated with a high performing building design process, as well as the specification writing process. Additionally, you must be a minimum of 18 years of age to participate.

We will use your experience and feedback to examine the building design process, information available for building material design decisions and work towards determining optimal methods for incorporation and utilization of building product data for high performing and healthy buildings. The content of this study is funded by the National Science Foundation Graduate Research Fellowship Program.

All of the information gathered including the focus group responses will be video recorded and will be held in the strictest confidence. However, due to the nature of focus groups, complete confidentiality cannot be guaranteed. Your participation in the focus group is voluntary. You can stop or leave at any time. The focus group will be expected to last less than 2 hours. A full explanation of the focus group process will be provided at the onset of the meeting. If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788.

The focus group is designed to share your experience with us (the researchers), as well as peers. As such, we anticipate that you will benefit from the interaction and contribute to improvement in our industry.

Sincerely,

Rebekah Burke
Rebekah.Burke@asu.edu
757-621-0522

Dr. Kristen Parrish
Kristen.Parrish@asu.edu
480-727-6363

School of Sustainable Engineering and the Built Environment
Arizona State University

Your signature documents your permission to take part in this research.

______________________________ _______________
Signature of participant Date

____
Printed name of participant

1. What is your profession?
- Engineer
- Architect
- Project Manager
- Interior Designer
- Other ____________________

2. How many years experience do you have working in the Architecture, Engineering and Construction industry?

3. How much experience do you have writing or editing building material specifications?
- A great deal
- A lot
- A moderate amount
- A little
- None at all

4. How many certified high-performing building projects have you worked on (any version of LEED, Green Globes, The Living Building Challenge, EnergyStar, EarthCraft)?

5. Have you completed, or are you currently engaged in, the design of a building pursing LEED 2009 (aka LEED v3) certification?
- Yes, I have completed the design of a building pursuing (or that has completed) LEED 2009 certification
- Yes, I am currently engaged in the design of a LEED 2009 building
- No
- Unsure

6. Have you completed, or are you currently engaged in, the design of a building pursuing LEED v4 certification?
- Yes, I have completed the design of a building pursuing (or that has completed) LEED v4 certification
- Yes, I am currently engaged in the design of a building pursuing LEED v4 certification
- No
- Unsure

7. Have you completed, or are you engaged in, the design of a building pursuing the Living Building Challenge certification?

- ❍ Yes, I have completed the design of a building pursuing (or that has completed) Living Building Challenge certification
- ❍ Yes, I am currently engaged in the design of a building pursuing Living Building Challenge Certification
- ❍ No
- ❍ Unsure

8. Have you completed, or are you engaged in, the design of a building pursuing Green Globes certification?

- ❍ Yes, I have completed the design of a building pursuing (or that has completed) Green Globes certification
- ❍ Yes, I am currently engaged in the design of a building pursuing Green Globes certification
- ❍ No
- ❍ Unsure

9. Have you or your design team utilized environmental performance information for building materials during the design process?

- ❍ Yes
- ❍ No

If you answered no to question 9, proceed to question 32.

10. What environmental performance information have you accessed regarding building materials?

- ❑ Environmental Product Declarations (EPDs)
- ❑ Cradle to Cradle (C2C) Certifications
- ❑ Life Cycle Assessment (LCA) Reports, Calculators, Software (i.e., Athena, Gabi, SimaPro, BEES, product data)
- ❑ Recycled Content
- ❑ Regional Content
- ❑ Certified Wood Declarations
- ❑ Volatile Organic Compound (VOC) Content
- ❑ Renewable Resource Content
- ❑ Other ____________________

11. Have you heard of Health Product Declarations (HPD)?

- ❍ Yes
- ❍ No

If you answered no to question 11, proceed to question 18.

12. How familiar are you with HPDs?
- ❍ I have utilized HPDs on my projects by requiring their inclusion in specifications
- ❍ I have utilized HPDs on my projects but they were not written in to specifications
- ❍ I have utilized HPDs on my projects for specific materials
- ❍ I have looked at the content of HPDs for building materials, but have not utilized them on my projects
- ❍ I have seen HPDs, but have not reviewed them
- ❍ I have not seen an HPD, but have heard of them
- ❍ Other ____________________

13. At what phase in the design process did you (or your design team) first review HPDs for any of the building materials?
- ❑ 0-10% (Pre-design)
- ❑ 10-35% (Preliminary design)
- ❑ 35-65% (Design development documents)
- ❑ 65-90% (Pre-final documents)
- ❑ 90-100% (Final construction documents)
- ❑ After final construction documents
- ❑ Other ____________________________

14. From your perspective, do you think HPDs provide valuable information or value to the building design process or final building design?
- ❑ Yes, HPDs provide valuable information or value to the building design process
- ❑ Yes, HPDs provide valuable information or value to the final building design
- ❑ No

15. Please provide a brief description of the valuable information or value you believe HPDs provide in the building design process or final building design.

16. Do you think there is value in reviewing HPDs early in the design process to inform the design regarding health implications of materials?
- ❍ Definitely yes
- ❍ Probably yes
- ❍ Might or might not
- ❍ Probably not
- ❍ Definitely not

17. Provide a brief explanation why, or why not reviewing an HPD early in the design process provides value.

18. Have you heard of Environmental Product Declarations (EPDs)?
- ❍ Yes
- ❍ No

If you answered no to question 18, proceed to question 25.

19. How familiar are you with EPDs?
- ❍ I have utilized EPDs on my projects by requiring their inclusion in specifications
- ❍ I have utilized EPDs on my projects but they were not written in to specifications
- ❍ I have utilized EPDs on my projects for specific materials
- ❍ I have looked at the content of EPDs for building materials, but have not utilized them on my projects
- ❍ I have seen EPDs, but have not reviewed them
- ❍ I have not seen an EPD, but have heard of them
- ❍ Other ____________________

20. At what phase in the design process did you (or your design team) first review EPDs for any of the building materials?
- ❍ 0-10% (Pre-design)
- ❍ 10-35% (Preliminary design)
- ❍ 35-65% (Design development documents)
- ❍ 65-90% (Pre-final documents)
- ❍ 90-100% (Final construction documents)
- ❍ After final construction documents

21. From your perspective, do you think EPDs provide valuable information or value to the building design process or final building design?
- ❑ Yes, EPDs provide valuable information or value to the building design process
- ❑ Yes, EPDs provide valuable information or value to the final building design
- ❑ No

22. Please provide a brief description of the valuable information or value you believe EPDs provide in the building design process or final building design.

23. Do you think there is value in reviewing EPDs early in the design process to inform the design regarding environmental implications of materials?

- Definitely yes
- Probably yes
- Might or might not
- Probably not
- Definitely not

24. Provide a brief explanation why, or why not reviewing an EPD early in the design process provides value.

25. Have you heard of Life Cycle Assessment (LCA) reports or tools for building materials (i.e., Athena, GaBi, BEES, SimaPro product data)? (This is NOT referring to Life Cycle Cost Assessment (LCCA))

- Yes
- No

If you answered no to question 25, proceed to question 32.

26. How familiar are you with LCA reports or tools for building materials (i.e. Athena, GaBi, BEES, SimaPro, product data)? (This is NOT referring to Life Cycle Cost Assessment (LCCA))

- I have utilized LCA reports or tools on my projects by requiring their inclusion in specifications
- I have utilized LCA reports or tools on my projects but they were not written in to specifications
- I have utilized LCA reports or tools on my projects for specific materials
- I have looked at the content of LCA reports or tools for building materials, but have not utilized them on my projects
- I have seen LCA reports or tools, but have not reviewed them
- I have not seen an LCA report or tool, but have heard of them
- Other _________________________

27. At what phase in the design process did you (or your design team) first review LCA reports or utilize LCA tools for any of the building materials?

- ❍ 0-10% (Pre-design)
- ❍ 10-35% (Preliminary design)
- ❍ 35-65% (Design development documents)
- ❍ 65-90% (Pre-final documents)
- ❍ 90-100% (Final construction documents)
- ❍ After final construction documents
- ❍ Other ________________________

28. From your perspective, do you think LCA reports and tools provide valuable information or value to the building design process or final building design?

- ❑ Yes, LCA reports and tools provide valuable information or value to the building design process
- ❑ Yes, LCA reports and tools provide valuable information or value to the final building design
- ❑ No

29. Please provide a brief description of the valuable information or value you believe LCA reports or tools provide in the building design process or final building design.

30. Do you think there is value in reviewing LCA reports or utilizing LCA tools early in the design process to inform the design regarding environmental and/or health implications of materials?

- ❍ Definitely yes
- ❍ Probably yes
- ❍ Might or might not
- ❍ Probably not
- ❍ Definitely not

31. Provide a brief explanation why, or why not reviewing LCA reports or utilizing LCA tools early in the design process provides value.

32. Does your firm, department or team have a policy or procedure (written or unwritten, formal or informal) to evaluate the environmental and/or health impacts of materials specified on projects?

- ❑ Yes, my firm has a written (or formal) policy or guidelines I use to evaluate the environmental and/or health impact of materials for all buildings we design
- ❑ Yes, my department or team, has a written (or formal) policy or guidelines I use to evaluate the environmental and/or health impact of materials for all buildings we design
- ❑ Yes, my firm has another department or specific person that is responsible to evaluate the environmental and/or health impacts of materials for all buildings we design
- ❑ Yes, my firm has a written (or formal) policy or guidelines I use to evaluate the environmental and/or health impact of materials for building designs that have client or certification driven requirements
- ❑ Yes, my department or team, has a written (or formal) policy or guideline I use to evaluate the environmental and/or health impact of materials for the building designs that have client or certification driven requirements
- ❑ Yes, my firm has another department or specific person that is responsible to evaluate the environmental and/or health impact of material for the building designs that have client or certification driven requirements
- ❑ Yes, my firm, department or team has a policy, but I am not familiar with it
- ❑ No, my firm, department or team does not have a policy or procedure
- ❑ I am not certain if my firm, department or team has a policy or procedure
- ❑ Other ____________________

33. If you would like the research team to send you results of this survey please provide your contact information below. Additionally, if we can contact you for feedback, or to share any of your responses with attribution please indicate in the appropriate check boxes below.

Name ______________________________________

Email ______________________________________

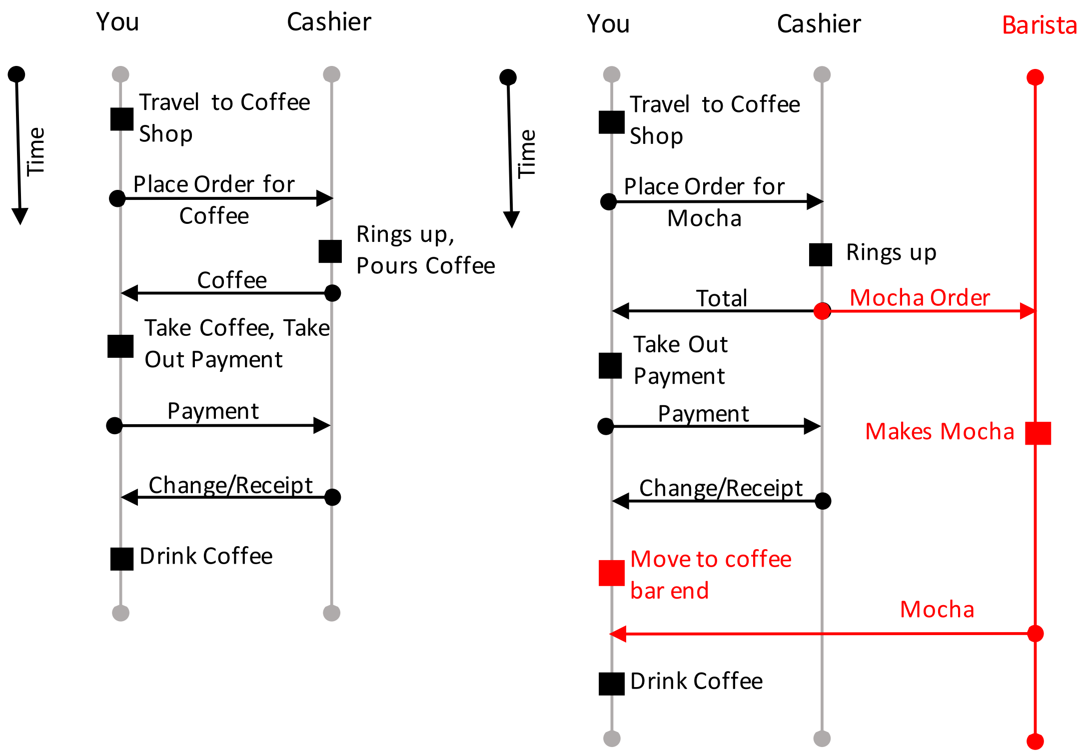
Phone Number ______________________________

You can contact me for:

- ❑ Provide survey results
- ❑ Additional feedback
- ❑ Share responses with attribution

APPENDIX C

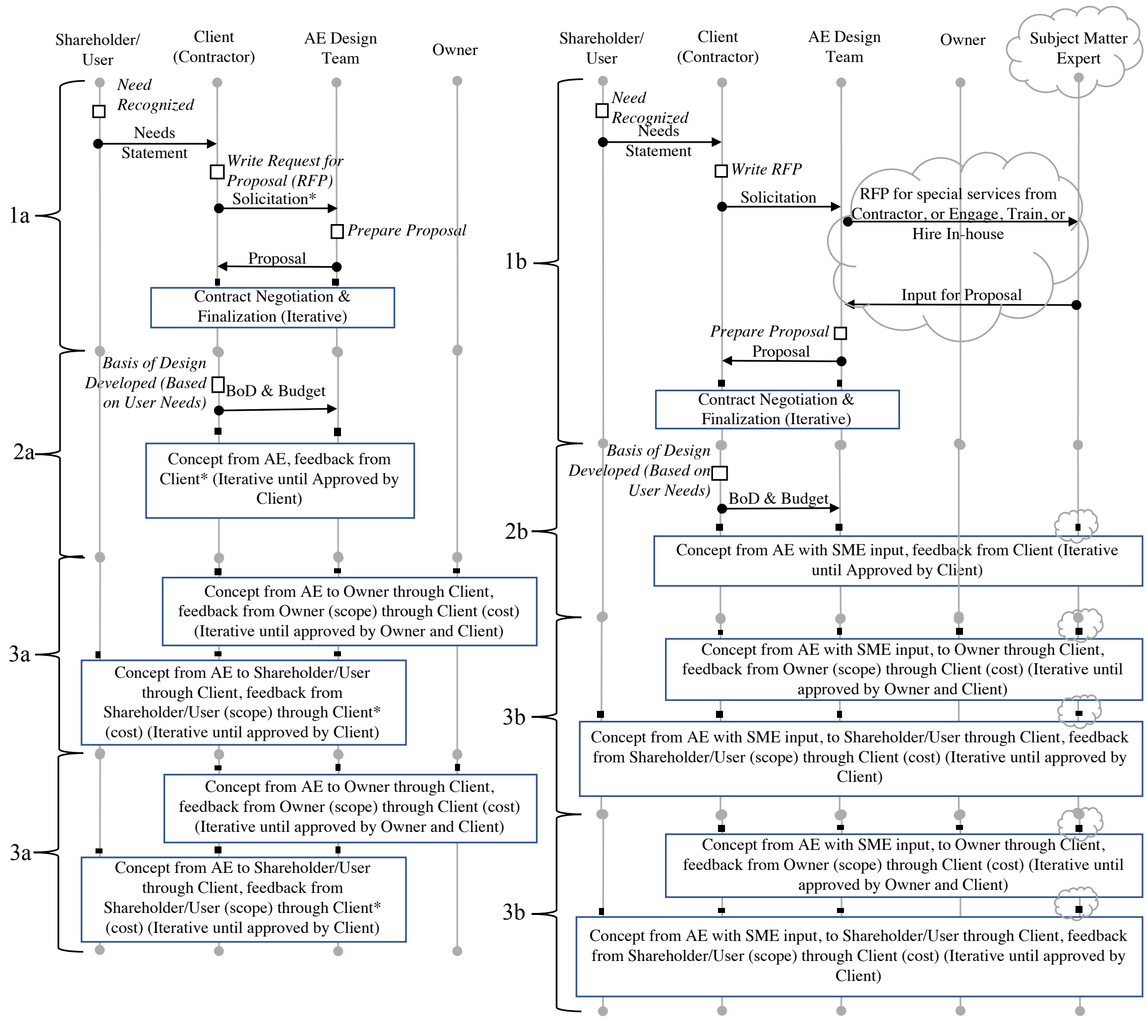
DEMONSTRATION OF MESSAGE SEQUENCE CHART (COFFEE VS MOCHA ORDER)



Example of a message sequence chart for familiarity. The left is a simple coffee order at a coffee shop, the right adds complexity to the order with a mocha, and shows the adjustments required in the MSC; an additional participant, additional actions, and additional transfers between the participants.

APPENDIX D

FULL MESSAGE SEQUENCE CHART FOR FOCUS GROUP MEMBER I1-06



The chart on the left corresponds to the full MSC that represents the initial conceptual design process as documented by participant I1-06 (coded in Table 12). The segment labels to the left correspond to Figures 10, 11, and 12. The chart on the right corresponds to the full MSC that represents the modified design process as documented by participant I1-06 when asked to add the consideration of an MSC to the design process in the most effective way. The bubbles on the right chart are denoting the modifications made in this instance.