ABSTRACT

Title of Dissertation INFLUENCE OF PROJECT DESIGN TEAM CHARACTERISTICS ON CONSTRUCTION COST OF SUSTAINABLE BUILDINGS

Ming Hu
Doctor of Philosophy, 2022

Dissertation Directed by Professor Miroslaw Skibniewski
Department of Civil and Environmental Engineering

Sustainability has become a driver of innovation in the built environment, but the affordability of sustainable building remains a significant challenge, according to developers, building owners, and design teams. This dissertation proposes a framework to understand how the characteristics of a project design team are influential cost drivers. We use empirical data to understand: (1) the sustainable building construction cost (SBCC) in relation to level of sustainability; (2) the influence on the SBCC of soft cost associated with the project design team; (3) the causal relation between project characteristics, project design team characteristics and construction cost of sustainable buildings. A mixed methodology is employed with four steps: research flow; a regression model and structural equation model in the quantitative research phases; and a comparative case study in the qualitative research phase. Altogether, thirteen project and project design team characteristics are studied, and ten hypotheses tested. The findings reveal: (a) the construction cost of studied sustainable building is comparable to conventional buildings, even lower; (b) the relationship between the construction cost and level of sustainability achieved is inconclusive; (c) among the project design team characteristics, skill and experience dominate, while communication, collaboration, and innovation are less influential; and (d) technical complexity is not always related to sustainability, hence the empirical data does not proved its influence. The proposed research contributes to research and practice at three levels: data, evidence, and methodology. The broad impact of this research is to advance an understanding of the SBCC cost as a means of promoting building green. The findings and methods resulting from this research project can empower architects, engineers, and developers to promote affordable sustainable building.

Keywords: project design team characteristics, project characteristics, construction cost, LEED buildings, structural equation model, case study

INFLUENCE OF PROJECT DESIGN TEAM ON CONSTRUCTION COST OF SUSTAINABLE BUILDINGS

by

Ming Hu

Dissertation submitted to the Faculty of the Graduate School of

University of Maryland, College Park in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

2022

Advisory Committee

Professor Miroslaw Skibniewski, Chair / Advisor
Professor Gregory Baecher
Professor Qingbin Cui
Professor Jungho Kim
Professor Jelena Srebric
Professor Ralph Bennett (Dean's Representative)

Dedication

Thanks to my husband Kai Hu, for his support and faith in me. Without his commitment, effort, and support, I could not have made it through this process. I appreciate the ability to focus on my studies into the late evenings and be able to stay with my work. I know how difficult this was for my family and I thank them for their understanding. Dedication also goes to my parents, my mother, Guang Ma and my father, Renlu Hu, for their patience and support over the past years. I dedicate to them this important professional achievement.

Acknowledgement

I would like to express my thanks to many that helped me through this process. There have been many little things and many large things that people have given as support over many years to be able to get me through the different stages of this doctoral program.

I sincerely give acknowledgement to my advisor, Dr. Miroslaw Skibniewski, without his time, patience, and guidance; this would not have been possible. He was able to help me with many different areas and kept the comments and information to the point and real. I appreciate the timeliness of responses from both Dr. Skibniewski during this process.

I would like to thank the other members of my Ph.D. committee, Dr. Gregory Baecher, Dr.Qingbin Cui, Dr. Jungho Kim, Dr. Jelena Srebric, and Professor Ralph Bennett. I appreciate your time, insight, and contributions to my learning journey. You all have added to my success during this dissertation process.

Thanks also goes out to my Dean, Dr. Donald W. Linebaugh and Dr. Dawn Eve Jourdan, my mentor Professor Madlen Simon from School of Architecture, Planning and Preservation, for supporting and sponsoring me during the journey.

I owe my deepest gratitude to my husband, my best critic and friend. I also want to thank my mother and father; it is their faith in me has kept me on the road to pursue knowledge. Words cannot express the gratitude and love I owe them.

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Acronyms

ARRA	American Recovery and Reinvestment Act of 2009
DB	Design-Build
DBB	Design-Bid-Build
EISA	Energy Independence and Security Act
EWGG	Edith Green Wendell Wayatt Federal building
GSA	General Service Administrative
IPD	Integrated Project Delivery
HMM	Howard M. Metzenbaum Courthouse
SCS	Sustainable Building Construction Cost Surcharge
SEM	Structural Equation Model
SBCC	Sustainable Building Construction Cost
WAF	Wayne Aspinall Federal Building

Chapter 1 Introduction

Chapter one introduces the research motivation and background of the dissertation, the problem statement, the research scope, and overarching questions. It also outlines the proposed research conceptual model and objectives. The structural organization of this dissertation is detailed to facilitate readers at the end.

1.1. Research Motivation

1.1.1 Experience from practice

While sustainability has become a key driver of innovation in the built environment (Prahalad & Rangaswami, 2009; Outram, Kelly, 2021), the affordability of sustainable building remains a significant challenge. Developers, building owners, and design teams often point to high construction costs as the primary obstacle hindering the uptake of sustainable buildings (Pitt et al., 2009)(Salvalai et al., 2015). In the 2018 SmartMarket Report, despite a decline in the past five years of the general perception of sustainable building as expensive, 49% of industry experts and professionals still think green building is expensive (*World Green Building Trends 2018 SmartMarket Report*, n.d.). This cost concern may remain as a top obstacle to the promotion of sustainable building in coming years.

The research topic for this dissertation is rooted in the researcher's professional working experience and academic research expertise in sustainable building design and construction. The researcher has in-depth knowledge of sustainable rating systems and years of experience working as a project designer and architect on many LEED certified sustainable buildings. Over time, the researcher has observed the positive and negative impacts that design teams have had on project costs and schedules. After each project, the researcher tried to better understand how the overall success of the project's construction cost control was either positively or negatively affected by the design team's decisions. The researcher has observed practitioners in the building and construction industry start a project with an assumption of the sustainable building cost and then consequently not focus on cost control at the same level as that in conventional buildings. The researcher has also observed design teams specify unnecessary expensive materials and products that do not directly contribute to the sustainability of the building, promoting the perception that sustainable building is more expensive. Such compounding causes directly contribute to a higher construction cost for sustainable buildings but are often ignored both in research and practice. The decisions made in sustainable building design are viewed influential to the final construction cost, but do not deterministic since the costs related to design decision-making represent less than 10% of total construction cost. Consequently, the project design team's impact is less studied and understood.

1.1.2 Market trends

There are multiple factors driving up the market demand for sustainable building. The first driver is the carbon emissions reduction goal. Building green has been recognized as one of the most effective strategies for overall energy consumption and carbon emissions reductions, and sustainable building has become common practice. As stated in the *World Green Building Trends 2018 SmartMarket Report*, organizations across the construction industry continue to shift toward more sustainable buildings and products (*World Green Building Trends 2018 SmartMarket Report*, n.d.).

The second driver is real estate profit. A recently published article in the *New York Times*, titled "As Risks of Climate Change Rise, Investors Seek Greener Buildings," reported that mutual funds and exchange-traded funds invested nearly $300 billion in sustainable assets globally in 2020, nearly double that of the previous year. As stated by the chief investment officer of a Dutch investment firm, "Today, you don't sacrifice returns for sustainability, you create returns with sustainability." The effects of climate change are indeed altering the strategies of investment trends. If older buildings don't lower their carbon footprint, they are likely to suffer from depreciation of their assets as early as in five years (2021) (Sisson, 2021). The third driver is legislation incentives. For example, the "Better Buildings" imitative of the U.S. Department of Energy (DOE) is designed to prioritize investments in affordable, safe, and efficient homes and businesses powered by reliable, clean energy. All these drivers will boost the demand for sustainable buildings.

While it is promising that the market will eventually catch up with the potential value of green buildings, a profit-driven investment approach not only leads to higher prices for green buildings but also potential greenwashing. In addition, it is worrisome that the pursuit of an investor- and market-driven approach may boost the perception of sustainable buildings as being expensive. The perceived high cost and market pursuit may further advance the reputation of sustainable building as an elite pursuit, eventually resulting in environmental injustice through pushing green building prices out of reach for low-income families and even middle-class families. To provide insights into the actual construction cost of sustainable building, this dissertation aims to address the perceptions, factors, and cost drivers associated with the green building construction cost and to deliver the notion that sustainble building for all is within reach.

1.1.3 Overarching research goal

An overarching research goal of this dissertation is to propose a framework to understand the project design team characteristics as influential cost drivers. Consequently, the newfound framework and knowledge can be used to make recommendations to improve the sustainable building construction cost (SBCC) control and even reduce the cost. To propose the framework, the researcher first needs to assess the cost factors and drivers of sustainable buildings using empirical data; therefore, collecting actual construction cost data is a critical task and contribution to this research. With the proposed framework, the causal relation between cost factors and the SBCC can be studied and understood. Additionally, since sustainability has been perceived as a main cost driver, using empirical data to analyze the relation between the level of sustainability and total construction cost will provide building users, policy makers, and the public with non-biased evidence of whether sustainable buildings are affordable.

The researcher took several steps to determine the validity of the topic. First, the researcher surveyed ideas on this topic through reviewing many areas of literature in a variety of subfields within the building and construction industry. In addition, the researcher interviewed sustainable design leaders in leading green design firms and green construction firms. Regarding published papers (refer to Chapter 2 Literature Review), fewer than five papers covered the design team's influence on the construction cost. The literature review indicated either an absence of a body of knowledge or a lack of research interest in the design team's influence on the construction cost. This lack of interest and studies is reasonable as the design cost typically represents a small portion of the total construction cost (<10%), drawing the focus toward larger costs, such as those of labor, materials, and equipment. However, the influence of design decisions cannot be ignored since the decisions affecting the project cost and schedule most are often made in the early stages of a project.

1.2 Description of the Problem

1.2.1 Lack of understanding of cost factors and drivers related to sustainable building

Regarding the drivers of sustainable building, Ramboll's *Sustainable Buildings Market Study 2019* showed the most important trends driving sustainable building activity are "Life cycle thinking and management" (71%), "Health and wellbeing" (58%), and Increased focus on carbon neutrality" (53%) (Ramboll 2019). Those top drivers are indeed **different from** those of conventional buildings, such as program needs and investment gains. Such differences can impact the project financial planning and cost-benefit analysis. However, the Ramboll report did not provide a detailed explanation of the differences or through which mechanisms those drivers shift the SBCC up or down. Both life cycle thinking and carbon neutrality call for low embodied carbon materials and building construction methods, which indicate local materials or less energy intensive methods. Logically, such drivers can lead to using more locally supplied materials that are affordable and familiar to local builders, consequently reducing the construction cost. This logical assumption contradicts the common perception of sustainable building being expensive.

To date, a large amount of research has focused on the benefits of sustainable building for users, clients, and society (Liu et al., 2014), such as incremental economic benefits through saving energy and improving the environment (Eichholtz et al., 2010). Gabay et al. (2014) pointed out how green labels affect the market rents and values of commercial spaces, potentially leading to a high resale value of a building. However, only a small portfolio of studies has investigated the cost obstacles (Y. F. Zhang & Fuh, 1998). Regarding costs related to public sustainable building, there is very limited literature and reports to date due to the difficulty of getting actual construction cost data. Meanwhile, despite the widespread perception of sustainable building being expensive, the existing empirical studies and evidence to support this claim are inadequate (refer to Chapter 2). Without a deeper understanding of the cost factors and drivers, creating effective strategies to control or reduce the construction cost is impossible. The ineffectiveness of certain current policies is a reflection of a lack of supporting empirical evidence. Although much anecdotal evidence has been collected based on case studies, these non-systematic data and analyses do not generate enough importance to capture people's attention on this important topic.

1.2.2 Lack of construction cost data

As stated by Chegut et al. (2019), access to a comprehensive and consistent set of data on building construction costs is remarkably hard to obtain. Therefore, a variety of data collection methods were employed. The most used method for acquiring data was contacting the project team and collecting construction documents (SCI 2011; Meron and Meir 2017); occasionally, the researchers reached out to the building operators or owners for information as well (GSA 2004). Such methods require a collaborative working relation between practitioners and researchers and are time-consuming as researchers must organize and comb through the data.

The second most used data collection method was questionnaires or surveys, sometimes followed up by one-on-one interviews (HIRL 2014). This method is the most practical and convenient, but it produces much variation due to a certain subjectivity. Some early studies conducted by industry experts and green consultants showed no or minimal SBCC surcharge without explaining the data sources or questions asked. Therefore, it was not clear whether the survey focused on the practitioners' perception of green building costs or actual green building construction. In addition, due to the nature of the survey questions, it was difficult to gain a deeper understanding of which building system and components were most influential for the SBCC surcharge and why.

Use of a cost estimator and a publicly available database were ranked as the third commonly used method for data collection. This method presents transparency and clarity. Most publicly available databases, especially those sponsored by the government, such as the United States Census Bureau and Israel's Central Bureau of Statistics (Dwaikat and Ali 2016), provide detailed information about how the data is collected and analyzed as well as metadata files. This public data is more transparent and reliable; furthermore, the same data collecting method can be replicated by other researchers or industry experts, which contributes tremendously to the consistency in construction cost studies. Cost estimator databases are not publicly accessible, and only one cost estimator's database (AECOM, formerly Davis Langdon) was used for four different studies for projects in the United States, Australia, and China (Hong Kong). This cost estimator's expertise, global practice coverage, and interest in practicing sustainable design may be why its database was primarily used. However, in the future, it will be beneficial to compare studies using data from different cost estimators' databases.

Overall, the data acquired from project teams, developers, and building owners is more reliable and accurate than that from other methods. For example, Shrestha and

Pushpala (2012) worked with local county public school districts to gain access to the actual construction costs of green and non-green school buildings. Altogether, 30 green school buildings and 30 non-green school buildings were studied, with the results showing the highest green building construction cost surcharge (46%) among all studies. Although the parameters that influenced the cost were not defined, the researchers suggested including a cost and construction control in future school project planning to control the high green cost surcharge (Dwaikat and Ali 2016). Their suggestion and insights were echoed and proven in the first large-scale net zero commercial project in the United States: the National Renewable Energy Laboratory (NREL). This building was completed in 2008 (phase one) and 2010 (phase two) with actual construction costs ($\$259/m^2$ and $\$245/m^2$) that were a third lower than those of a typical commercial construction of similar size and type in the United States (Torcellini et al. 2015). The successful strategies identified for cost control from this project were two: the *competitive procurement process* and *the integrated decision-making proces*s in the early design stages. The client (NREL) incorporated measurable performance goals into the project request for the proposal; therefore, when the team bid on this project, they treated the listed sustainability goals as a indispensable requirement within the allowed budget. After selecting the project team (include contractors and designers), NREL also integrated trade partners into the overall decision-making process in the early design stages to ensure that construction considerations were properly weighed during the design. Moreover, all the stakeholders agreed on the design decisions and related construction cost implications. Such an integrated approach is particularly useful for green building, where a certain number of sustainable practices and technologies are not familiar to all team members. Those unfamiliar technologies may contribute to a cost increase because risk and uncertainty are usually associated with a cost increase (Amiril et al. 2017).

1.2.3 Variety and differences in sustainable building

The current terminology that describes sustainable building rating systems, certificates, assessments, and related tools is inconsistent and unclear. A large body of research has examined the differences between rating systems. For example, Haapio et al. reviewed 16 different building environmental assessment systems, including Leadership in Energy and Environmental Design (LEED), Athena, Building Research Establishment Environmental Assessment Method (BREEAM), Envest, BEAT 2002, Eco-Quantum, and Annex 31. The key issues identified were the understanding of the tools and how these tools have affected decision-making in building green. Gou and Lau conducted a study on differences in green building certification systems at international, national, and local levels by choosing three green rating systems: HK-BEAM, China Green Building Label, and LEED V4. They explained the differences between the rating systems by using the conceptualism theory, which can be traced back to the fundamental divergence in lifestyles, preferences, and urban morphology, besides climatic variations (Gou & Lau, 2014). Nguyen and Altan compared five sustainable rating systems: BREEAM (UK), LEED (US), Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan), GREEN STAR (Australia), and HK-BEAM. The results indicate that BREEAM and LEED scored the highest based on nine criteria (Nguyen et al., 2012). Fowler and Rauch gave an overview of sustainable building rating systems with a focused comparison of five rating systems—BREEAM, CASBEE, GBTool, Green Globes™, and LEED—based on communicability, verification, measurability, technical content, system maturity, usability, development, and applicability. They concluded that rating systems need to address several important elements, such as the large scale and complexity of federal building projects and the need to track quantifiable achievements (Fowler, Kimberly M., and Emily M. Rauch, 2006).

Two summaries can be concluded from the large body of studies comparing various sustainable building rating systems. First, there is similarity among the rating systems: 70% of the existing comparative studies focus on four leading rating systems: BREEAM, LEED, CASBEE, and China Three Start, which were developed geographically in the United States, the United Kingdom, Japan, and China (Doan et al., 2017). Among those different rating systems, there are three common categories: *energy efficiency*, *material resources,* and *indoor environment* (Doan et al., 2017).

Second, there are significant differences between the rating systems, which may lead to differences in buildings' actual performance. For example, Asdrubali et al. (2015) compared LEED (US) and ITACA (Italy) for residential buildings using two buildings located in Italy. Their findings revealed that for materials, LEED analyzes the number of components made from recycled materials used in construction, while ITACA is based on the number of components that are recyclable at the end of a building's life cycle. For indoor environmental quality, LEED includes more criteria than ITACA, giving special weight to the environmental effect of the construction phase (Asdrubali et al., 2015). Consequently, higher constraints are placed on the construction phase, which can influence the construction cost, method, and schedule. These differences in the rating systems' impact on cost have not been addressed sufficiently since the existing studies focus more on rating systems' impact on building performance. Several studies focused on how the construction cost related to the sustainable building score and credits, and certain existing research used a simulated (estimated) building cost (AlAwam & Alshamrani, 2021) or secondary data from a literature review (Tatari & Kucukvar, 2011). Very few studies used a large firsthand data set of actual building costs.

Overall, the lack of a consistent definition and measurement of a building's sustainability increase difficulties in understanding the construction cost implications. Further, ambiguity around the cost factors and drivers for sustainable building hinder efforts to reduce the cost and thus promote the adoption of sustainable buildings.

1.3 Research Theoretical Background and Overarching Question

1.3.1 Theoretical background

One of the most influential concepts regarding construction time and cost control is the effort curve, commonly known as the MacLeamy curve, which describes the relation between cost and change through the project stages. The effort curve was popularized by Patrick MacLeamy in 2004, but its origins were published by Boyd C. Paulson Jr. in 1976 (Paulson, 1976). In a paper titled "Designing to Reduce Construction Costs" he first presented a diagram illustrating the level of influence on project costs (Refer to Figure 1.1). Paulson's first insights were that the decisions and commitments made during the early phases of a project (engineering and architectural design) have a orders of magnitude on later expenditures. His second important observation was that efforts to suboptimize design costs by requiring competitive bidding for professional services were likely to produce much higher project costs in the long run (Paulson, 1976).

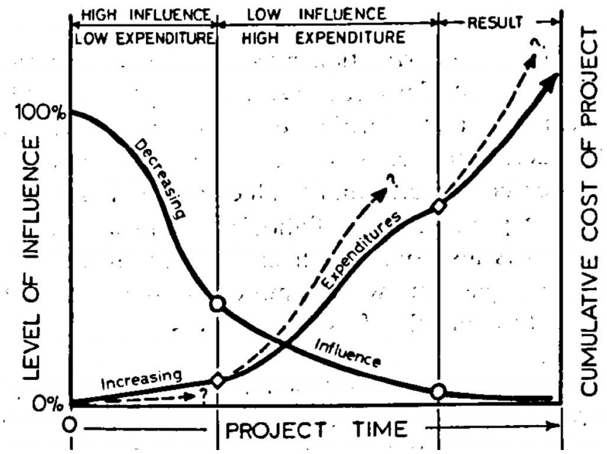


Figure 1.1 Project effort curve (Paulson, 1976)

Since the publication of his concept paper in 1976, Paulson has become known for his involvement in large federally funded construction projects, such as the U.S. urban rail projects BART, in Northern California, and Metrorail, in Washington, D.C. He also volunteered to oversee construction of Peninsula Habitat for Humanity's $2 million, 24-unit condominium project for low-income residents in California (Shwartz, 2005). Other researchers and practitioners tried to adopt and promote the project effort curve proposed by Paulson, but little attraction was gained until the early 2000s.

The two notions are adopted in this book to explain the influential design team characteristics and project characteristics of the early project stages (pre-design and schematic design) to the final construction cost. The hypothesis is that the project team characteristics in the early project stages will have a large impact on the final construction cost. Because the cost of making changes in late project stage has higher cost in the sustainable building compared to conventional building due to the constraints of sustainable building. Logically, the success and effort made in the early project design stages can be assumed to be more influential and impactful.

1.3.2 Research scope and overarching questions

The overarching question addressed by this book is: Does the design team's capability have a causal effect on the sustainable building construction cost (SBCC)? If so, to what extent? To answer the research questions, this dissertation intends to propose a framework (illustrated in Figure 1.2) to investigate and explain the SBCC with a causal relation to project characteristics, design team characteristics, and the level of sustainability.

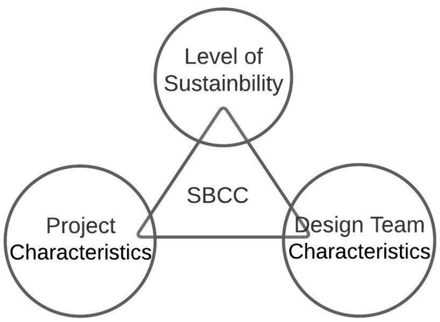


Figure 1.2 SBCC explanatory framework

1.3.3 Specific research objectives

This research project uses empirical data to understand (1) the SBCC in relation to the level of sustainability, (2) the influence of soft costs related to the design team to the SBCC, (3) the influence of the project design team's characteristics to the SBCC, and (4) the underlying reason for the influential project team characteristics. To gain such an understanding, the specific objectives of the project are as follows:

Objective 1: Determine the global status of the SBCC.

Objective 2: Investigate the soft costs' (associated with the design team) impact on the total construction cost**.**

Objective 3: Evaluate the pattern of correlation/covariance among project characteristics, project team characteristics, and the level of sustainability to the SBCC.

1.4 Proposed Research Conceptual Model

To test the framework illustrated in Figure 1.2, a conceptual model is created that hypothesizes the pattern of correlation and covariance among the set of constructs that have an impact on the construction cost. The four main constructs examined in this dissertation research are derived from the framework: project team characteristics, project characteristics, level of sustainability, and the sustainable building construction cost. Figure 1.3 illustrates the hypothesized causal relations among these four constructs: a straight line with an arrow represents a causal relation, a curved line with an arrow represents covariance, a "+" sign represents a positive influence, and a "-" sign represents a negative influence. The following sections explain each construct.

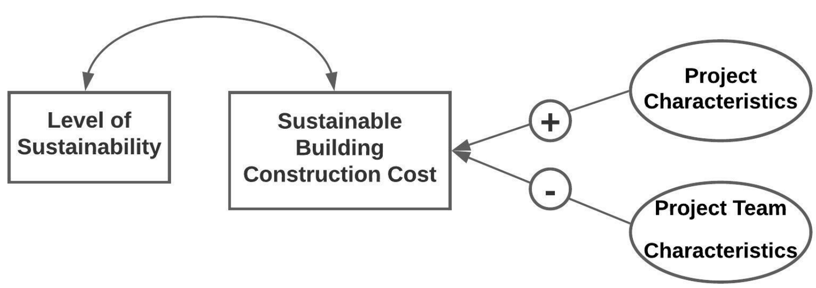


Figure 1.3 Proposed conceptual model and constructs

1.4.1 Project characteristics

Project characteristics mainly focus on project physical and technical conditions. For the project physical conditions, building types, construction types, and project scale are important influential factors (Sovacool et al., 2014) (Hwang & Low, 2012). In addition, the researcher also wants to focus on other important characteristics, such as technical complexity and supply chain maturity, which were speculated as influential factors to the conventional building construction cost from a conducted survey (Y.-M. Cheng, 2014).

The exact definition and index used to measure the project characteristics are derived from the meta-analysis conducted by the researcher as the first phase of this dissertation study. The findings of the meta-analysis are included in Chapter 4.

1.4.2 Design team characteristics

In general, studies focusing on the design team's influence are limited because these factors are more difficult to conceive due to their indirect and hidden nature. Although some sources have supported the construction cost being related to the design input (fee to design teams) in construction projects, the influence of the design cost itself has been sporadically discussed (Cheng, 2014).The limited studies indicated that the skill and experience of the project manager and contractors are influential factors to the total SBCC (Cho et al., 2009). Survey data also suggested that design complexity was somewhat influential to the building construction cost (Chen et al., 2012). The potential interpretation is that the design team's skills and experience can mediate the negative effects of technical complexity on the construction cost of sustainable buildings.

The design team characteristic investigated in this project focuses on the design team; specifically the design team's *skill levels, experience, motivation to innovate, communication, and collaboration.* The reason why these variables are used to present the project team characteristic are explained in Chapter 4.

1.4.3 Level of sustainability

In this study, the level of sustainability (LOS) is defined by the credits or level of certification received from the LEED rating system. LEED certification has four levels: Certified, Silver, Gold, and Platinum. To achieve each level, certain points are required, but the numbers of points required for the same level varies depending on the LEED rating system and which version is applied to the projects. For example, the current LEED v4.1 for Building Design and Construction (LEED BD+C) has a maximum of 110 points, and to achieve Certified, at least 40 points are required. Silver requires 50–59 points, Gold requires 60–79 points, and Platinum requires 80 or more points. However, the third version of LEED BD+C, released in late 2005, only has a total of 69 available points, where 26–32 points are required for Certified, 33–38 points for Silver, 39–51 points for Gold, and 52–69 points for Platinum. Furthermore, LEED v4.1 O+M, Existing Buildings Operations and Maintenance, has a total of 100 points, but the certification level is the same as LEED BD+C. The projects included in this study are certified under a different rating system and/or under a different version.

1.4.4 Construction cost

In this study, the researcher includes hard costs and soft costs in the construction cost. Hard costs are defined as a type of direct cost that can be traced back to the physical components or activities of the construction project, which includes the land cost, labor, materials, equipment, and the overhead cost from the contractor and developer (Ade & Rehm, 2020). In this study, the land cost and site cost are excluded. Soft costs are defined as the items not directly related to the physical construction of the buildings but that are necessary for the administration of a building project (Zahirah et al., 2013). Soft costs cover a wide range of cost items, from administration fees, design fees, and auditing fees (Ade and Rehm 2020) to certification, commissioning, marketing, and taxes (Zahirah et al., 2013). Soft costs are mostly related to and affected by project team characteristics. Together, the hard costs and soft costs comprise the construction cost of a building.

1.5 Research Significance

This study on SBCC as an independent topic will cultivate in-depth knowledge of sustainable building practices, consequently creating a research framework/method to examine construction cost-related sustainability barriers. This investigation of broader cost drivers beyond the project variables (e.g., project team characteristics) will represent one of the few studies examining the construction cost issue through the design team's perspective. To this end, the proposed research will fill three knowledge gaps. ***First***, the SBCC database will provide large increase in the quantity of public accessible empirical data. Previously, theories have been validated with small data sets or have not been validated at all. ***Second***, the case studies will provide information on the cost variance of sustainable buildings in a way that differs from that of conventional buildings. ***Third***, the use of structural equation modeling (SEM) with actual sustainable building cost data will represent the first rigorously tested quantitative and qualitative combined model that focuses on the factors influencing the SBCC. By providing a means of quantifying sustainable buildings' affordability, the research will give traction to the "green for everyone" philosophy that has been widely discussed yet narrowly implemented.

1.6 Dissertation Organization

The following chapters of this dissertation are organized as follows. Chapter 2 provides a comprehensive overview of the existing body of knowledge on the SBCC in the context of influential factors, regional differences, and cost variables. Knowledge gaps in the SBCC are identified, and the SBCC surcharge is defined as well. Chapter 3 explains the research approach and methodology employed in this dissertation, and four research phases are outlined and described. Chapter 4 focuses on phase one of the research: the meta-analysis results. First, the global status of the SBCC surcharge is presented, and differences per region, building type, and data sources are outlined. Then, the project characteristic variables and project team variables that are influential to the construction cost are extracted from the meta-analysis, laying the foundation for further examination of regression model and SEM analyses. Chapter 5 focuses on phase two of the research: the SBCC database creation. The data sources and collection procedure are described, and a summary description of the data is also provided. Chapter 6 centers on phase three, where the quantitative analysis results are explained. A regression model and SEM are used to test 10 hypotheses; then the results are presented, and the findings are discussed. The findings from the statistical analysis presented in Chapter 6 call for further investigation. Therefore, Chapter 7 analyzes three built projects, representing low-, median, and high-cost brackets, and focuses on the mechanism of how project team characteristic impact the total construction cost. Insights and further explanations are offered based on project team statements, online interviews, and other qualitative data of the three case projects. In Chapter 8, the researcher first reviews the research problems and then concludes the dissertation with a summary of findings, contributions, implications, and suggestions for future research directions.

Chapter 2 Literature Review

This chapter is dedicated to the review of literature on sustainable building construction costs. The aim is to provide a better understanding of research activities around this topic, knowledge gaps and trends. To understand the sustainable building construction cost, we ought to first have an overall understanding of building construction cost. The researcher first outlines the research activities in the last three decades in building construction cost in general, the knowledge gaps are identified and described. Then the researcher examined the components included in a building's construction cost estimation and the terminologies used. After discussion about building construction cost, the focus then switches onto sustainable building construction cost. The components, current research status and gaps related to sustainable building construction cost are discussed at the end.

2.1 A Scope Review of Research Activities on Building Construction Costs

Before the 1980s, there were very few scientific research publications that focused on building construction costs, regardless of building construction cost estimations already being a relatively established field in practice. The earliest record on building construction cost can be found in online database is "Volume and cost of building construction, 1914 to 1924 published on Monthly Labor Review (Byer, 1925). From 1925 to 1980, there was only six publications found on the topic of construction cost. Among the six publication, three focused on general building construction cost, one on school building construction cost, and one on apartment building construction cost. The rest one was titled "Energy cost of building construction" published in 1977, that was the first known published study on embodied energy cost of building construction in the United Stated (Stein, 1977). Starting from early 1980, there has been increasing research activities of building construction costs. As illustrated in Figure 2.1, we can divide those actives into three periods: phase one (1980 to 1990), phase two (1991 to 2005), phase three (2005 to 2021). Blue line represents the publication of conventional buildings, orange line represents the publication on green buildings.

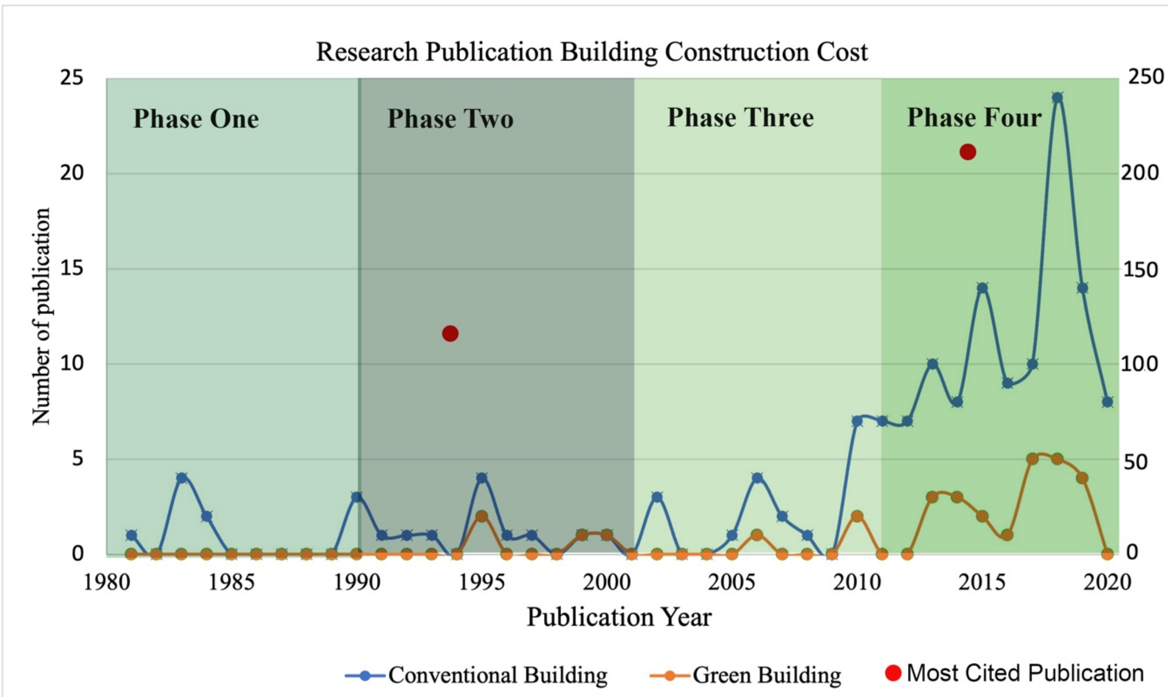


Figure 2.1 Publication on building construction cost and green building construction cost

2.1.1 Phase one: 1980 - 1990

From the early 1980s to the 1990s, there was a steady increase in publications, total 10 publications, and most publications were from trade or professional organization publishers. Five out of ten publications were published on Architecture Record, which is the primary trade association publication of Architects in the United States. Two studies were published as conference proceedings by International Council for Research and Innovation in Building and Construction (CIB). And the topic of research focused on the overall housing price fluctuations or construction cost forecast rather than cost factor analysis, and very few studies were published as independent academic research. One interesting observation can be found was the two peak publication year of construction cost study aligned with the economic recession time, 1981-1983， 1990-199. Such observation can be explained by the building construction industry was one of the industry hit harder by the recession, hence there were needs and incentives from the industry and professional organization to conduct their own study and cost forecast analysis. Overall, in this ten-year period time, the research activities around building construction cost were dominated by industry and trade organization.

2.1.2 Phase two: 1991-2000

From the 1990s to 2005, 11 publications were found. Those publications demonstrated two trends in research activities on building construction cost. First is the emerge of construction cost study of green buildings. In the early 1990s, sustainable or green buildings were not well defined, so publications related to green building costs were often titled as "cost of CO_2 reduction." For example, one of the earliest studies published in 1995 used a parametric cost model to study the construction cost increase and CO_2 emissions reduction by replacing non-sustainable building materials (cement) with sustainable building materials (lime) (Tiwari & Parikh, 1995). The researchers found that a 21% emissions reduction produced a 27% increase in building construction costs that was mainly related to materials and labor costs (Tiwari & Parikh, 1995). The concept of life cycle cost saving from green building was also introduced in this period, in 1999, Journal of Construction Engineering and Management published a paper titled “Selecting cost-effective green building products: BEES approach”, that is one of most cited studies regarding cost of green building products till today. Later in 2000, Architectural Record also published a short article introducing Building for Environmental and Economic Sustainability (BEES) software developed by National Institute of Standards and Technology (NIST). BEES measures economic performance using the ASTM standard life cycle cost method, which covers the cost of initial investment, replacement, operation, maintenance and report and disposal of building materials (Lippiatt, 2000). BEES was developed in 1994, but it started to be known by design community only from 2000, after the publication of the two articles.

The second trend is the increasing activities from academic researchers. Five publications were from academic researchers, and six publications were from trade associations or practitioners. And most publication from academic researcher focused on green building cost while publication from industry focused on cost estimating, advanced methods and tools. For example, the concept of parametric construction cost estimation of buildings was first introduced in a study presented at 1993 Transactions of AACE International: 37 Annual meeting”. AACE International is the Association for the Advancement of Cost Engineering.

The main difference of research topics between phase two and phase one was that the majority (8 out of 11 publication) of phase two research activities has been focusing on construction cost factors and cost optimization / reduction.

2.1.3 Phase three: 2001 – 2010

Phase three saw steady increase of interest in building construction cost study, but not in sustainable buildings construction cost, out of total 18 publications, there are only 3 publications mentioned green building construction cost. However, during this period, the tremendous increase of activities can be observed from academic researchers. 14 publications out of 18 were from academic researchers. The large number of academic researchers can potentially explain why most studies were based on hypothetical value or responses from survey / questionaries (Love, 2002), since it is not likely easy for academic researchers to acquire the actual project construction cost data. Such difficulty remains the primary obstacles for building construction cost related studies till today.

2.1.4 Phase four: 2011 – 2021

Around 2010, there was a major jump in interest in building construction cost research, especially in conventional buildings, however the increase study in sustainable buildings' construction cost has remained relatively low. Total there are 111 publications on conventional building construction cost, while only 23 on sustainable building construction cost. From 2010 to 2020, a variety of cost factors were investigated besides the material and labor costs; multiple regression was a commonly used technique (Lowe et al., 2006). Also, during this period, there was an overlapping between conventional building construction cost research and sustainable building cost research. One of the most cited papers, "Construction cost comparison between green and conventional office buildings," was published in 2013 (Rehm & Ade, 2013), however, the majority of such comparisons are based on expert interviews or surveys (Rehm & Ade, 2013). The real project construction data was still lacking.

Different from the previous phases, two major research trends can be observed. First, after 2015, there has been increasing interest in improving research methods to gain a more quantitative understanding of how the conventional building and sustainable building construction costs are affected. Presumably, because of the lack of actual building construction cost data, the focus was turned to the cost estimation comparison. There has been an exponential increase in exploration to integrate and introduce new tools, models and methods in traditional construction cost estimations and analysis. New methods and tools include the Monte Carlo simulation (Raydugin, 2017), stochastic annuity method (Fregonara & Ferrando, 2020), neural network model (Chandanshive & Kambekar, 2019) and BIM-based construction cost estimation (Akanbi et al., 2019). They have been applied in both conventional and sustainable building construction cost estimations and analysis. The second research trend in phase four was the shift within the sustainable building construction cost research. There was increasing interest in building life cycle cost analysis, rather than initial construction cost. Among the publication published after 2015, ten out of thirteen green building construction cost was focusing on life cycle cost.

In the phase four, the most promising trend in the past five years is the use of real project construction cost for study. For example, Sun et al (2019) obtained cost data of 37 green building-certified residential buildings and 36 general residential building from public accessible data sources. Their results show the average construction cost of a sustainable residential building was only 1.58% higher than a general residential building, that provided solid evidences of sustainable buildings do not necessary more expensive than conventional buildings. However, they also found achieving high level of sustainability (certification level) is associated with an increase of 6.7% to 9.3% in construction costs.(Sun et al., 2019). More data from actual built projects can provide researchers and practitioners a deep dive into the most influential components and factors, and further study the potential causes to the perception of green building being costly. In the following sections, more detailed explanations are provided for changes in cost component and cost estimation methods, based on the time sequence outlined above.

2.1.5 Summary of research activities

In the past several decades, substantial increase research activities can be observed on the topic of building construction cost, especially in the last decade (2010-2021), but, the growth of research in sustainable building constructions cost is limited. As illustrated in Figure 2.2, the primary research leader switched from industry and practitioners to researchers. As for the research topics, there are wide range of topics, from the new cost estimation method to control of cost overrun, but the primary research method has been survey and interview and data have been mainly qualitative. The lack of the actual building construction cost data has been a barrier for decades for research on building construction cost in general. Moreover, the lack of data also contributes to the slow growing interest in studying sustainable building construction cost, since sustainability has been view as a brand with technical difficulty and high price tag. Consequently, the lack of quantitative study are closely tied to the wide-spread perception of the sustainable building being expensive without robust empirical evidences. Another general knowledge gap observed is studying of design and human impact on construction cost, since the dominating focus has been on construction method, labor/material supply and construction management.

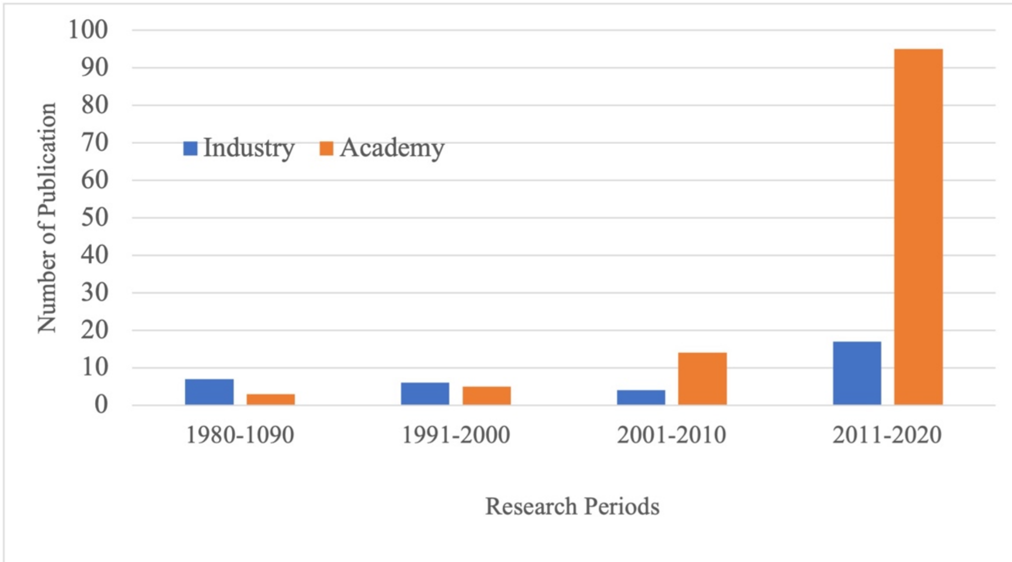


Figure 2.2 Studies by industry and academics

Based on the two general findings derived from the past several decades of research activities. In the following sections, researcher wants to focus on examining the previous studies on sustainable building construction cost (in comparison to conventional buildings) to get a sense whether the previous literature is sufficient for researcher to derive cost factors to be included in further analysis. In addition, the researcher wants to dive into the commonly used cost components, and the hope is to gain the insight into why the quantitative data are difficult to get, besides the reason that the construction cost data is typically the propriety information of the building owners.

2.2 Current Research Status Focusing on Sustainable Building Construction Cost (SBCC)

2.2.1 Literature selections

After gaining an overall picture of research activities on building construction cost, the researcher wants to focus on the sustainable building construction cost research activities in past decades. To date, there has been a large number of studies focusing on the benefits of sustainable building for users, clients, and society. These studies have focused on the operating savings and potential resale value using cost-benefit analysis. Liu et al., (2014) estimated that sustainable building could create incremental economic benefits by saving energy and improving the environment, while other studies showed how green building labels (certification) can affect the market rents and values of commercial spaces, potentially leading to a high resale value of a building (Eichholtz et al., 2010) (Torcellini et al., 2015). Further, a relatively large body of publications focused on the life cycle cost of sustainable buildings, with a research aim to quantify the economic benefits of sustainable building through savings during the operation stage (Dwaikat & Ali, 2018). Even though those literature mentioned above addressed important cost issues of sustainable building and had empirical data, this proposed dissertation research focuses on the construction cost of sustainable buildings; therefore, the literature did not specifically address the construction cost are excluded from further examination. The literature included was selected based on the following criteria: (i) the publication addresses the sustainable building construction cost as the main research topic, (ii) the publication relies on empirical data to draw a conclusion, (iii) the publication specifies the cost data resources, and (iv) the publication calculates the sustainable building cost compared to that of conventional building cost in percentage, where the percentage difference is defined as the sustainable building cost surcharge (SCS), calculated using Equation 1)

SCS = additional SBCCs/conventional building construction cost (Eq. 1)

Where additional SBCC include hard and soft costs (refer to section 2.5), conventional building refers to those buildings not certified through any sustainable building certifications. The buildings included in the previous studies differ in climate condition, function, construction type, location, and source of data. The data sources vary widely, from questionnaires (surveys) to actual construction documents. Consequently, it is not appropriate to directly compare the cases against each other. The cases also differ in size and estimated lifetime. To neutralize these differences, the construction cost figures were normalized per unit of area ($/m^2), and then compared in percentages of the additional SBCC in relation to the conventional building cost.

2.2.2 Findings and conclusion

Table 2.1summarizes a comprehensive literature review on the results and data sources of SBCC-related studies. The literature review showed that only a small portfolio of studies investigated the SBCC factors, variance, and obstacles, and the results were highly varied.

Table 2.1 Existing literature on sustainable building construction cost-related publications and data sources

Publication	Country	Year	Case Study #	Type of Building	Area (m^2)	SCS (%)	Data Source	Conduct by
Xenergy and Sera Architects	USA	2000	1–3	OF	230–1,432	-0.3%–1.3%	Actual cost data from project team	Industry
Kats et al.	USA	2003	33	SH, OF	NA	-0.66%–6.5%	Survey response (primary architects)	Industry
Matthiessen & Morris	USA	2004	93	AC, LB	NA	No significant difference	Cost estimator database	Industry
Steven Winter Associates (GSA)	USA	2004	2	OF	26,200–30,600	-0.4%–8.2%	Internet search	Industry
Bradshaw et al.	USA	2005	16	RES	400–7,390	-18.33%–8.15%	Literature review and internet search	Industry
Kats	USA	2006	30	SH	NA	0%–6.27%	Actual cost data from project team	Industry
Green Building Council Australia	Australia	2006	8	OF	NA	12–22%	Australian Green Building Council private database	Industry
Matthiessen & Morris	USA	2007	221	AC, LB, SH, OF	NA	No significant difference	Cost estimator database	Industry
Davis Langdon	Australia	2007	3	OF	>15,000	3%–11%	Cost estimator database	Industry
Construction Industry Institute	China (Hong Kong)	2008	38	OF	NA	0%–3.2%	Construction cost handbook (China & Hong Kong 2006) and cost	Industry

							estimator database	
Fullbrook & Woods	New Zealand	2009	4	AC, HO, SH, OF	3000	1.25%–6.23%	Actual cost data from project team	Industry
Houghton et al.	USA	2009	13	HA	2,800–47,000	0%–5%	Survey response and interview	Academia
Kats et al.	USA	2009	155	RES, HA, HE, SH, LAB, OTHERS	240–200,000	0%–18%	Survey response (primary architects)	Industry
Mapp et al.	USA	2011	10	BANK	281–512	< 2%	Actual cost data from project team	Academia
Zhang et al	China	2011	3	Hotel, OF, RES	33,610 – 23,710	8.5%–13.9%	Actual cost data from project team	Academia
Shrestha and Pushpala	USA	2012	60	SH		No significant difference	Actual cost data from project team (Clark County School District)	Academia
Nyikos et al	USA	2012	160	ALL	NA	0.66% to 6.5%	Online search	Academia
Rehm and Ade	New Zealand	2013	17	OF	NA	No significant difference	Actual cost data from project team	Academia
Building Research Establishment (BRE)	UK	2014	3	OF	13,800	0%–5.7%	Survey response	Industry
NAHB Research Center	USA	2014	6	RES	232	0.68%–14.65%	Survey response	Industry
Kim et al.	USA	2014	2	RES	270	10.77%	WinEstimator database and 2011	Academia

							RS Means estimator	
Gabay et al.	Israel	2014	6	OF	1,000–10,000	4.4%–11.6%	Israel Central Bureau of Statistics	Academia
Alexeew et al.	India	2015	4	RES	NA	0.8%–2.8%	Modeled cost	Academia
Garcia et al.	USA	2015	8	RES	95–248.3	13.7%–36.9%	Modeled cost	Academia
Dwaikat and Ali	Global	2016	17	ALL	NA	-0.4%–21%	Literature review	Academia
Hwang et al.	Singapore	2017	363	ALL	NA	4.5%–7%	Survey response (from project design)	Academia
Yih Chong et al.	Malaysia	2017	6	RES	NA	2.2%	Modelled cost	Academia
Chegut et al.	UK	2019	542	ALL	NA	6.5%	The Royal Institution of Chartered Surveyor's BCIS database	Academia
Sun et al.	Taiwan	2019	74	RES	2,085–122,097	-19%–9.3%	Government public information websites and architectural professional magazines	Academia
Ade and Rehm	New Zealand	2020	10	RES	NA	3%–5%	Author's own practice data	Academia
AC: Academic OF: office SH: School RES: Residential HA: Healthcare LAB: Laboratory								

As illustrated in Table 2.1, the SCS varies between quite a lot, between -18.33% and 36.9%, and the empirical data used for study differs between studies published by academic researchers and industry experts.

Some existing studies show that the cost of sustainable building has high premium costs. Kim et al. (2014) revealed a 10.77% increase in the sustainable residential building construction cost compared to that of conventional buildings not complying with green building codes. The researchers believed that the cost impact from the green building code was due to the incorporation of alternative power sources and energy-efficient appliances and equipment; the base building cost increase was not significant. In another study, Shrestha & Pushpala (2012) analyzed the construction costs and speed of thirty green school buildings and compared the results to another thirty non-green schools. The authors comparatively concluded that the green school buildings cost 46% more than their conventional counterparts, and mean construction costs per square foot of the green schools were significantly higher than that of conventional schools. In a study published by the National Association of Home Builders (NAHB) research group, a case study was conducted to itemize the cost impact of applying the National Green Building Standard to a green home, and they concluded that the cost premium was around 14% for a silver-level certified house (Home Innovation Research labs, 2014). One thing worth to note is that the construction cost data used in those studies are estimated data using R.S.Means Residential Cost Data book. And the method they used to calculate the construction cost of sustainable building is to add additional green cost to the similar conventional buildings, which is guaranteed to results in higher construction cost. Those studies have not taken into consideration that added cost of increased insulation or energy efficient fixtures can be offset by the downsizing the mechanical equipment, therefore using the same conventional building cost as a base will not reflect the real cost of a sustainable building.

In contrast, other studies and findings indicate that green buildings can be achieved at a very low cost premium. In the best-case scenario, there is no significant cost difference between sustainable buildings and conventional buildings. One of the most influential studies was commissioned by the Sustainable Building Task Force in the state of California and conducted by a group of sustainable consultants as well as experts from a federal agency and national laboratory. They analyzed thirty-three LEED buildings, with analytic data showing that the median SCS was around 2%, or close to $4/ft2, which is substantially less than what is generally perceived (Kats et al., 2003). The study also concluded that sustainable buildings cost less—on average, 30% less—to operate and maintain. In a later study, Kats(2006) investigated the design and construction costs of thirty green schools in different places in the United States and concluded that, on average, the SCS of green schools was around 2%, compared to conventional schools. Another important study that has been cited widely was conducted by a professional cost consulting company, Davis Langdon. They conducted studies in nineteen different counties and collected datasets of almost six hundred buildings. The building types included academic buildings, classrooms, laboratories, offices, hospitals, libraries, theaters, sports facilities, and museums. Their conclusion was that many projects achieved the sustainable goal without adding additional costs to their initial budget (Matthiessen & Morris, 2004). Another interesting study they carried out was a point-by-point analysis of sixty-one LEED-seeking projects. They found that those sixty-one projects were able to meet the LEED certification without an additional cost. In a later study of a total of 221 buildings (with 83 of them being LEED-seeking projects and the other 138 buildings not having such sustainable goals), they concluded that many projects were achieving LEED within their budgets and in the same cost range as non-LEED projects. The study also determined that the main obstacle to promoting sustainable building was not cost but the idea that **green is an added item** (Mathiessen & Morris, 2007).

Besides the different results on whether sustainable building has additional construction cost, thee are clear division caused by the who conducted the analysis. Of the studies, 65% were conducted by industry experts and published by trade organizations, professional associations, or green building certification organizations. The data collection and research methods of these studies were typically not well defined or explained in the publications. Furthermore, the studies by industry experts are older, with most published before 2010 and only three studies published after 2010. On the contrary, most of the academic publications were published after 2010 (Dwaikat & Ali, 2018); only one study was conducted and published before 2010. The mean green surcharge cost from the academic research is 10.2%, which is much higher than that of the industry-associated published studies, at 3.06%. It is understandable that in the early period, the primary cost data resources were gathered by industry experts, particularly professionals working in the green building field. The research and reports based on empirical data demonstrating the wide range in cost variance require further studies and research.

The results from the literature review show a wide range in cost variation of sustainable buildings, which did not provide an adequate indication of the cost components and whether there is a definite additional cost for sustainable buildings. Such wide-range variation reflects the heterogeneity of the commercial building stock. There are many factors that could cause these differences, such as building use (retail, office, hotel, education, etc.), building location (labor cost, material availability), climate and site conditions, and technologies and systems used in the buildings. Since the current literature review is not sufficient, therefore a meta-analysis is needed to get a clearly understanding the cost components, factors of sustainable building additional compared to conventional buildings, and such analysis needs to have breakdown by building types, locations, and cost data resources, and who conducted the analysis. Based on such summary, a meta-analysis is included in research phase one in this dissertation.

2.3 Cost Categories and Components Definition Change Through the Time

For the cost unit used, a variety of terminologies are used: first cost, capital cost, investment cost (Green Building Council of Australia, n.d.), direct cost, indirect cost, hard cost, and soft cost. The most commonly used pairs of cost components are direct cost/indirect cost and hard cost/soft cost. Soft cost and hard cost are terminologies adopted for this study, in the following sessions, the items included in those cost categories are examined.

2.3.1 Direct costs vs. indirect costs

Carr was the first to clearly define direct costs as the costs that are traceable to physical activity (Carr, 1989); therefore, it is not a direct cost if an activity has not been performed (Houghton et al., 2009). The indirect costs are business costs other than the direct cost of construction activities; they are not physically traceable and are counted even if the activity is not performed. An indirect cost is also known as overhead (Houghton et al., 2009). The Association for the Advancement of Cost Engineering International (AACE) defined direct costs as those resources that are expended solely to complete the activity or asset. The direct cost includes the cost of materials, labor, and equipment, while the indirect cost (overhead) consists of project overhead, general overhead and other transactional cost. Project overhead includes the costs that are economically traceable to a project, such as a superintendent's salary and a tower crane rental. Small items and tools, such as nails and wires, are also considered project overhead. General overhead includes general office overhead, which is not typically traceable to construction activities or a project but is necessary for operating an office and obtaining work and other administrative work. Such overhead includes general office and warehouse rentals, insurance, salary, and others (refer to Table 2.2).

Table 2.2 Direct and Indirect Cost breakdown (adopted from AACE manual, 6th edition)

Categories	**Items**	**Sub Items**
Direct	Material	
	Labor	Contractors
		Design professional
	Equipment	
	Permit fee	
Categories	**Items**	**Sub Items**
Indirect	Project overhead	Labor (superintendent salary)
		Equipment (tower crane rental)
		Materials (nails, wires, etc,)
	General overhead	General office/admin. salary
		Office rental/ warehouse rental
		Tax / insurance
		Office supplies

2.3.2 Variable costs vs. fixed costs

Another way to classify the construction cost is to differentiate the costs as variable costs and fixed costs (Lowe et al., 2006). This is a similar method used with accounting principles. Concrete work can be measured in square feet (meters), dry wall work can be measured in linear feet (meter), and site work can be measured in cubic yards (meters). Since the costs vary as the quantity of work changes, they can be considered variable costs. Fixed costs are those costs that must be provided and are independent of the volume of work activity. These costs remain the same despite the change of work quantity and volume (Morris & Hough, 1987). For instance, the cost to rent a tower crane per day is fixed regardless of how much work is performed. Typically, project and general overhead—such as general office rentals, administrative costs, taxes, and salaries—are fixed costs. Both variable costs and fixed costs can be direct or indirect costs. Such terms also used to describe and analysis the cost prior to more supplicated methods being introduced around 2005.

2.3.3 Hard cost and soft cost

Compared to other cost definitions, the hard costs and soft costs were introduced to the building construction industry later and they are more broadly defined. Geltner et al. (2001) defined hard costs as a type of direct cost of the physical components of the construction project, which include labor, materials, equipment, and overhead costs from the contractor and developer. Soft costs include the design, legal fees, and financing. Zahirah et al. (2013) defined soft costs as referring to items not directly related to the physical construction activities but that are necessary to the administration of a building project. They defined six soft cost elements: consultants, green building consultants, certification, commissioning, marketing, and taxes (Zahirah et al. 2013)

2.3.4 Initial cost and life cycle cost

The initial cost, or capital cost, sometimes has been used interchangeably with the construction cost. Fuller defined the initial cost as a capital investment that includes land acquisition, construction costs (or renovation) and the equipment costs needed to operate the building (Fuller & Crawford, 2011). Qian & Foogn included all costs associated with procurement, supply, transport and installation in the initial cost (AY Qian, 2013). In general, the initial cost includes the construction cost but goes beyond the costs associated with construction activities.

Life cycle cost analysis was first introduced to evaluate green building material and product studies. In 1995, the National Institute of Standards and Technology (NIST) published the Life Cycle Cost Manual (Handbook 135), which was developed for use in performing life cycle cost analysis (LCCA) of investments in federal buildings and facilities (AY Qian, 2013). According to Handbook 135, the life cycle cost includes the initial investment, the annual cost for operation, maintenance and repairs. In later research, building demolishing and deconstruction costs were included as well (Gopanagoni & Velpula, 2020). Even with the early developments in the life cycle cost method and manual, the adoption of and interest in life cycle cost estimation in the building and construction industry were negligible. Even to date, the practice of LCCA in construction projects is not common. Research interest in LCCA gradually started in early 2010, mainly in green building construction costs. Understandably, the lack of interest in life cycle costs from the construction industry is caused by split incentives. The developers, contractors and design teams only bear the costs of and benefit from the initial capital investment. The life cycle cost benefit is more related to the building operators and occupants, who typically are not part of the team that makes the capital investment decisions.

2.4 Knowledge gaps in construction cost and estimation in general

There are three research gaps in the construction cost of a building: (1) misuse of cost and price (2) lack of cost estimation transparency, and (3) lack of definition of construction cost of sustainable building.

2.4.1 Misuse of cost and price

First, most existing literature on construction costs does not provide a clear definition about the types of costs and sometimes does not differentiate the building costs from the resale price. Carlston (1952) draws a distinction between building prices and building costs by referring to the former as the market price for building work payable by a client and the latter as the costs incurred by a contractor in carrying out work. In general, the price always reflects some consideration of profits, while the term cost normally does not include profit. But sometimes price is used to derive the cost if the profit factor is known. For example. The U.S. Census Bureau estimates the construction cost of new single-family houses using housing starts and/or sale data from the U.S. Census Bureau's Survey of Construction (SOC). According to the SOC, the total cost of a private new single-family home is obtained by multiplying the number of units by the average construction cost per unit. For units built by the developer (to be sold or rented), the average construction cost is the average sales price at the time of start multiplied by the factor 0.8424. This factor eliminates an estimate of the cost of "nonconstruction" items, such as raw land, marketing costs, closing costs, profit, and movable appliances (United States Census Bureau, n.d.). For a home built for the owner, the total cost is the average contract value at the start of construction multiplied by the factor 1.102 to eliminate "nonconstruction" items and add the value of land development not already accounted for. Therefore, the national statistics for construction costs of residential units are derived from the sale price regardless of the type, which could lead to inaccurate information about the real construction cost. In addition, such complicated and varied calculation methods cause confusion, leading to difficulty in creating a fair comparison. One recent example demonstrates the confusion around price and cost of sustainable buildings. An article published in New York Time titled "California's plan to make new buildings greener will also raise costs" (Ivan Penn, 2021) using the sale price backtrack the construction cost and assumed the additional solar panel, less than 5% total actual building construction cost will be responsible for the sharping rising sale price of new single-family house. The sale price increase is influence by many factors, housing demand and supply, market trend and other unpredicted social and environmental condition (such as COVID-19). It is not reasonable to attribute 20% sale price increase all to the additional construction cost which is less than 5% increase. In addition, the author of the article completely ignored the long-term utility saving the homeowner can benefit from the solar electricity and relative short payback period. The mismatch or misuse of sale price to represent the construction cost is not only misleading, also has created huge barrier to promote building green.

2.4.2 Lack of cost estimation transparency

Second, there is no literature on generally accepted estimation guidelines, nor are consistent terminologies used for the construction cost estimation. The existing literature primarily focuses on estimating the format and procedures and the process for a particular application (Carr, 1989). There is limited attention on establishing a consistent estimation framework. Even though there is considerable literature on estimating principles proposed by researchers, common methods used in the industry have not reflected recent research findings. More precisely, there is no translation from research findings to practice regarding the construction cost estimation.

Association for the Advancement of Cost Engineering (AACE) does provide some guidelines for cost estimation. According to AACE, there are five levels of estimation that are primarily associated with project maturity: levels 1 through 5. The different levels of estimation entail different estimation methods. Generally, the estimation methods can be classified into two broad categories: conceptual and deterministic. As the level of project maturity increases, more project information is available, and the estimating method tends to progress from conceptual methods (stochastic or factored model) to deterministic methods. There are two factors that differentiate conceptual methods from deterministic methods. The first major difference is that in conceptual methods the data or factors used are not a direct measure of the building being estimated, while deterministic methods use data taken from the estimated building. Related to the data difference, conceptual models require significant effort to gather the historical data prior to cost estimation; then, the gathered historical data are used to develop factors and estimating algorithms. On the contrary, deterministic methods require a large effort during the estimation to measure the quantity and volume of the data taken from the actual building.

Table 2.3 Construction cost estimation methods and levels (adopted from AACE)

Estimated Level	Maturity Level of Project (% complete design)	Method	Expected Accuracy	End Usage (purpose of estimation)
1	65%–100%	deterministic	-10% to +15%	Final bid / tender
2	30%–75%	deterministic	-10% to +15%	Bid / tender
3	10%–40%	deterministic and/or conceptual	-20% to +30%	Budget authorization
4	1%–15%	conceptual	-30% to +50%	Feasibility study
5	0%–2%	conceptual	-50% to +100%	Concept screening

Conceptual methods are typically used for levels 4 and 5 and sometimes for level 3. The purpose of providing a conceptual estimation is to determine an approximate potential project cost without a detailed design or clearly defined scope of work in a relatively short time. It is also used by owners and developers to evaluate whether the project or investment can meet the financial thresholds, enabling strategic decisions and establishing the project's preliminary funding. There is a wide range of methods and techniques used, such as the end-product unit method, project comparison method, physical dimensions method, and parametric method. The guideline only provide a high-level principles and instruction, there is no agreed upon method or techniques specified by AACE. In addition, because the cost estimation database, tool, or even method are normally proprietary property of cost estimators or owners. There is rarely publicly available data and studied can be found from practitioners that explain the cost and cost estimation.

2.4.3 Lack of definition of construction cost of sustainable building

Lastly, there is no consensus or standard definition of the construction cost of a sustainable building (Houghton et al., 2009; Dwaikat & Ali, 2016). Dwaikat and Ali (2016) pointed out there were few academic studies published on the topic of sustainable building construction costs, and all of the studies were published recently, following 2010. They also concluded that there was no clear methodology describing sustainable buildings' additional construction costs compared to conventional buildings. Data availability and transparency have been identified as primary barriers to studying construction costs, particularly sustainable construction costs (Chegut et al., 2019). A lack of clear methodology describing sustainable buildings' construction costs is also identified as the leading cause for ambiguity and the large variation in costs of sustainable construction (Chegut et al., 2019). Houghton et al. (2009) defined the additional first-cost of green building as the additional construction costs associated with green design and construction elements, but he did not provide a detailed explanation.

2.5 Proposed cost components definition for sustainable building

The lack of a comprehensive understanding of the SBCC is related to the ambiguity of definition of construction cost components and insufficient data. There are many methods for calculating the construction costs, and these differences are reflected in the related empirical data on record. To have a consistent definition and reliable comparison, in this study, the researcher use the terms: hard cost an soft cost. Even though direct and indirect costs are the most commonly used definitions, they have a disadvantage related to a misperception about indirect costs. Indirect costs are often described as overhead, so the project manager often tries to reduce and control overhead to make the project economically viable (profitable) since the term indirect can be associated with non-necessary or unimportant. For this reason, the researcher believe using the hard and soft cost definitions can avoid unnecessary bias.

As the sustainable building has gradually become the accepted new standard and near-term goal, discussions regarding hard and soft costs of sustainable buildings have started to gain attraction from the practice and research community. Kats (2003) identified soft costs as the primary reason for the increase of the cost of green buildings. Mapp et al. (2011) studied bank buildings and defined soft costs as the costs associated with the design, engineering, consulting fees, and certification fee, among others. Their results demonstrated that LEED buildings did not experience any additional soft costs related to sustainable design practices (Mapp et al. 2011). Even though some researchers state that the soft costs can contribute up to 26–29% of the overall construction costs (Ade and Rehm 2020), however, due to the lack of studies, in general, soft costs, such as the design cost, considered only account for a small portion of the total construction cost, around 3–5% (Kats 2006). However, they still play a significant role, since most soft costs are capital costs and are borne by the developers upfront. Therefore, they have an immediate impact on the decisions of developers and builders to build green (Langdon 2004). In this study (refer to Table 2.4), hard costs refer to the cost items required and directly related to physical construction activities of sustainable building, and soft costs refer to items not directly related to physical activities but that are necessary for completion of the activities. The land cost is excluded in this study.

Table 2.4 Proposed construction cost components and definition used in this study

Hard Cost	
Material	
Labor	Contractor
	Design professional on-site
Equipment	
Overhead cost	Developer
	Contractor
Soft Cost	
Professional service fee	Architect / engineer
	Sustainable consultant
Administration fee	General office / inspection /management

2.6 Chapter Summary

This chapter first summarizes the research activities on building construction cost in the past decades, that was divided into four phases. The research and knowledge gaps are identified. After understanding the overall research activities of building construction cost in general, the researcher focuses on the current research status of sustainable building construction cost, trends and weakness are outlined. The ambiguity of use of cost terminology is identified as one of the research weakness that leading to the some misperception of the total construction cost of building. At the end, a pair of construction cost terminologies (soft cost and hard cost) are selected for this dissertation study and reason for selection are explained.

Chapter 3 Research Approach and Methodology

Chapter three focuses on research approach and methodology of this dissertation. First, the research philosophical worldview adopted in this dissertation is explained. The overarching research philosophy determine the research strategy selected, that is Explanatory sequential mixed method. Guided by such strategy and methods, this dissertation research is composed of four phases, and the purpose, tasks and objectives of each research phases are explained in this chapter. Chapter 3 serve as an instruction manual to help reader to understand the research approaches, strategies and methods used in this dissertation study.

3.1 Research Design and Strategies

3.1.1 Research philosophical worldviews

Research philosophical worldviews guide researchers in choosing the research approaches and methods (refer to Figure 3.1), therefore it is important to explain what worldviews the research is taking for this dissertation study.

"I see worldview as a general philosophical orientation about the world and the nature of the research that a researcher brings to a study. What view arise based on the discipline orientations,…, and past research experience….". "This information will help explain why they chose qualitative, quantitative, or mixed methods approaches to their research" (Creswell, 2017, p.35)

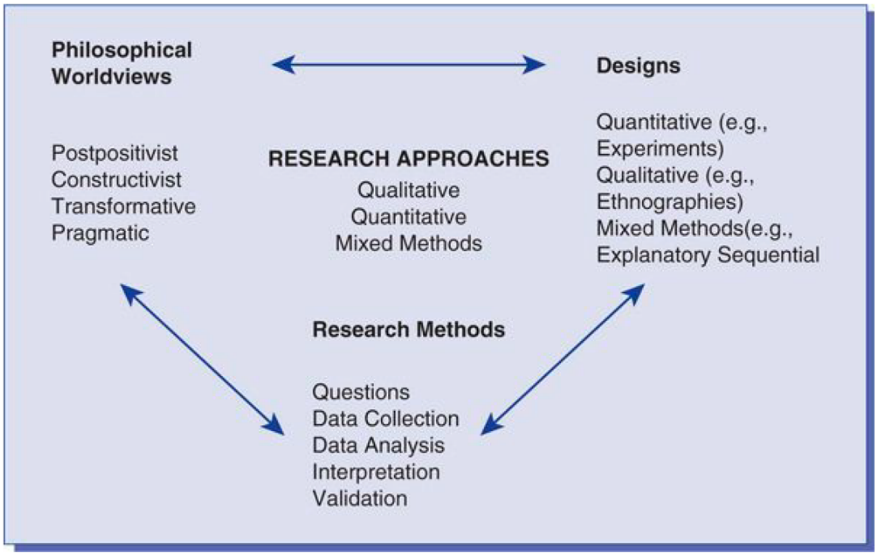


Figure 3.1 Framework for research (Creswell 2017, Figure 1.1)

Creswell outline four types of philosophical views listed in Figure 3.1, among them the pragmatic philosophical worldview is the most appropriate for this research since this dissertation research topic is real-world practice oriented and problem centered. Pragmatic researchers focus on research problems and look to the what and how to research based on the intended consequences. Pragmatists do not see the world as an absolute unity. In a similar way, mixed methods researchers tend to employ variety methods for collecting and analysing data. Therefore, the mixed-method approach is selected for this dissertation study.

3.1.2 Research approaches

Under the philosophical views, three research approaches are introduced by Creswell (Creswell & Creswell, 2017): qualitative, quantitative and mixed method, and they are rigid and distinct categories. The distinction between qualitative research is that the use of words (qualitative) rather than numbers (quantitative), and use of close-ended questions(quantitative), rather than open-ended questions (quantitative) (Creswell & Creswell 2017).

Qualitative research is an approach for exploring and understanding the meaning individuals or groups ascribe to a social or human problems (Creswell & Creswell, 2017). "*The process of research involves emerging questions and procedures, data typically collected in the participants settings, data analysis inductively building from particulars to general themes, and the research are making interpretations of the meaning of the data." (Creswell, 2009, p.32)*

Quantitative research is an approach for testing objective theories by examining their relation among variables (Creswell & Creswell, 2017). "*These variables, in turn, can be measured,…so that numbered data can be analysist using statistical* procedures." (Creswell, 2009, p.32)

In this dissertation, the researcher choose the mixed method approach, that is an approach to inquiry involving collecting both quantitative and qualitative data, integrating the two forms of data, and using distinct designs that may involve philosophical assumptions and theoretical frameworks (Creswell & Creswell, 2017).

"The core assumption of this form of inquiry is that the combination of qualitative and quantitative approaches provides a more complete understanding of our research problem than either approach alone." (Creswell, 2017, p.32)

Mixed method approach is relatively new compared to quantitative and qualitative approach, with major work in developing it stemming from the middle to late 1980s. The motivation to apply mixed method is to mitigate the weakness and bias resided in the individual method. The collection of both to quantitative and qualitative data, and the convergence across both data and methods are furthered developed and discussed in early 1990s till 2010s. Among the variety mixed methods, explanatory sequential mixed method is employed in this dissertation research. As illustrated in Figure 3.2 **Explanatory sequential mixed method** is the method in which the researcher first conduct quantitative research, analyzes the results and then builds on the results to explain them in more detail with qualitative research. Such method is especially suitable and popular in the field with strong quantitative orientation, such as engineering and construction. This method is also suitable for the type of research questions does not have existing theories or limited theories and knowledges. As explained in Chapter two, previous and current studies around SBCC is limited and non-systematic. There is no existing theories or limited theories regarding the drivers for sustainable building construction cost (SBCC). The key challenge is to identify the quantitative results to further explore and the unequal samples sizes for each phase of the study (Creswell & Creswell, 2017).

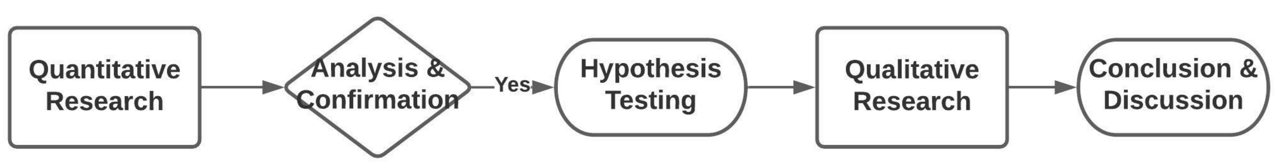


Figure 3.2 Explanatory sequential mixed method

Figure 3.2 demonstrates the logic and sequence of an explanatory sequential mixed method used in this dissertation. First, starting with quantitative research, after collecting the construction cost data, the regression model allows the researcher to examine the influence of soft cost and hard cost on the total construction cost. Soft cost is associated with project team characteristics, hard cost is associated with project characteristics. The regression model also allows researcher to examine influential variables among soft and hard cost components. After confirming the influence of project team characteristics to the total construction cost, Structural Equation Model is then used to test the hypothesis regarding those influential project team characteristicsvariables' causal relation to the construction cost. At the end of quantitative study, 10 hypotheses are tested, in addition, proposed cost framework is validated, and the influence of each variable is quantified. Next, move into qualitative stage**,** in order to gain better understanding of the mechanism how those project team characteristics variables influence the construction cost, Comparative case study method is employed with tree projects representing low, median and high cost bucket. Lastly, derived from the findings of both quantitively and qualitative studies, discussion is made, and conclusion is drawn.

3.2 Research Method Selection

As described above, a set of concurrent mixed methods were adopted, they are meta- analysis, regression analysis, structural equation model (SEM) analysis, and case study.

3.2.1 Meta-analysis

To understand the use of meta-analysis, it is useful to differentiate it from systematic review. A systematic review is an overview of primary studies which contains an explicit statement of objectives, materials, and methods (Ganeshkumar & Gopalakrishnan, 2013), and the interpretation of systematic review is often objective. Unlike systematic review, a meta-analysis is a mathematical synthesis of the results of previous studies that addressed the similar hypothesis in the similar way (Ganeshkumar & Gopalakrishnan, 2013). In another word, meta-analysis is the statistical procedure for combining data from multiple studies. It is often used as mechanism to synthesize data and results across studies, since individual studies, are most often small and may not directly lead to significant results, and yet they may contribute collectively to an outcome, or a new body of knowledge. The term of meta-analysis was generally agreed coined in a 1976 publication (GLASS, 1976).

Meta-analysis refers to the analysis of analyses . . . the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings. It connotes a rigorous alternative to the causal, narrative discussions of research studies which our attempts to make sense of the rapidly expanding research literature.

Meta-analysis has been used in variety field as a research tool since then. In building and construction field, it was used to quantify levels of wasted time in construction (Horman & Kenley, 2005), to study international construction project risk factors related to the host country (Aydogan & Köksal, 2014). Recently, meta-analysis was employed to study some new topic in construction industry. For example, it was used to study the development of building information model in the African Architecture, Engineering and Construction industry (Saka & Chan, 2019). Mariam et al., (2020) combined scientometric analysis and meta-analysis to research on women's health and safety in construction in order to identify the trend of research development. As related to sustainable building and construction, the use of meta-analysis is relative recent activity. It was used as effective research tool to understand the barriers to the adoption of modular integrated construction at global scale. Over 120 barriers in 15 countries in 5 continents were identified, and strategies to overcome the barriers were also proposed (Wuni & Shen, 2020). One most relative publication related to this dissertation was published in 2020 by Adolpho Guido et al., (2020). They reviewed over 2,600 papers on the topic of sustainable construction management, mixed methods were employed including meta-analysis. Their findings showed that first articles related to the topic of sustainability in construction field were published in 1993 and that among the studies found in Web of Science only 2.54% used quantitative methodologies to assess the sustainability of the construction industry. Such findings validate the need for quantitative research in sustainable building construction, in addition, it also proved that the sustainable building construction cost is an emerging field. To the researcher's knowledge (based on the literature review), to date, there is no meta-analysis has been conducted on sustainable building construction cost besides researcher's own publication (Hu & Skibniewski, 2021).

3.2.2 Quantitative method

Quantitative method includes two categories: experimental designs and nonexperimental design. This dissertation research employs nonexperimental research design techniques where investigators use the correlational statistic to describe and measure the degree or association (or relationship) between two of more variables or sets of scores (Elizabeth A Curtis, 2015). Such method has been elaborated into multilevel complex relationships among variables found in techniques of multivariable regression, structural equation modelling, hierarchical linear modelling, and logistic regression.

Regression model

Regression model can be used to study the correlation between the independent and dependent variables. It does not prove of disapprove the causal relation between independent and dependent variables, therefore it is appropriate to be used in this dissertation to study the relation between construction cost of sustainable building (SBCC) and the level of sustainability (LOS). The hypothesis is that there is no correlation between SBCC and LOS.

Structural Equation Modeling (SEM)

Structural Equation Modelling (SEM) is a comprehensive statistical technique that examines the hypotheses of the relationships between observed and latent variables (Fornell & Larcker, 1981). It can access a sequence of interdependent associations between the dependent and independent variables in a measurable way. The use of SEM is common in the natural sciences, especially in ecology and evolutionary biology (Sales et al., 2015) (Mitchell, 1992). Structural equation model has also been used as an effective and versatile research tool to study built environment quality, satisfaction and related occupant behavior, both indoors and outdoors (Leung et al., 2020)

However, SEM as a research tool has not been widely used in building construction and construction cost related research. There are very few examples. For example, (Patel & Jha, 2016) use SEM analyzed the empirical data of effect of safety climate, hazard management, safety budget, safety rules and regulations, and safe work behavior of employees and workers' safety performance on projects. SEM was also used by (Alaloul et al., 2020) to study the construction project performance based on coordination factors. Since SEM is more effective in measuring the direct and indirect influences of latent variables, and in this dissertation the cost drivers are latent variables reflected on the observed data, therefore, it is very appropriate to choose SEM as quantitative method. Moreover, from statistical point of view, conventional statistical methods employ one statistical test at a time to determine the significance of the analysis. But in SEM, researchers can utilize several statistical tests to determine significance and the adequacy of model fir to the data simultaneously.

3.2.3 Qualitative method: case study

There are variety types of approaches in qualitative research, that have been intensely developed during the 1990s and into 21st century study (Creswell & Creswell, 2017), such as narrative research (Lieblich et al., 1998), phenomenological research (Moustakas, 1994), grounded theory (Strauss & Corbin, 1997), ethnography, and case study (Stake, 1995).

Comparative case studies is selected for this dissertation project. It is a design of inquiry can be found in many fields, especially evaluations, in which the researcher develops an in-depth analysis of a case, or a group of cases. Cases are bounded by time and activities, and researchers collect detailed information using a variety of data collection procedures over a sub stand period of time (Stake, 1995)(Aberdeen, 2013). Case study research can includes both single and multiple cases (Aberdeen, 2013). Case study is preferable method for the researcher who want to answer "how" and "why" questions (Aberdeen, 2013). Since this dissertation research aims to better understand the causal relation between the project team characteristics and total construction cost, studying single project will not be sufficient, hence comparative case studies is chosen. Comparative case studies involve the analysis and synthesis of the similarities, differences and patterns among studies cases (Goodrick, 2014). A key differentiating feature between comparative case studies and case study is that comparative studies focus on generating explanatory claims and the requirement for theory and evidence-informed case selection (Goodrick, 2019).

3.3 Research Phases Plan

Based on the outlined explanatory sequential mixed method, the research phase and flow were planned. As illustrated in Figure 3.3, the proposed research is comprised of four phases. The theory and the elements contributing to the mechanism of how project team characteristics influencing construction cost are extracted and summarized from the meta-analysis. The hypothesized negative and positive relationship between project team characteristics and project characteristics to SBCC is based on the meta-analysis results as well. Regression analysis is used to test the hypothetical correlation between SBCC, project team characteristics (index by soft costs) and LOS. A conceptual SEM model is developed to depict the mechanism of project team characteristics affecting the SBCC. Case study is used to validate the path and factor findings from SEM.

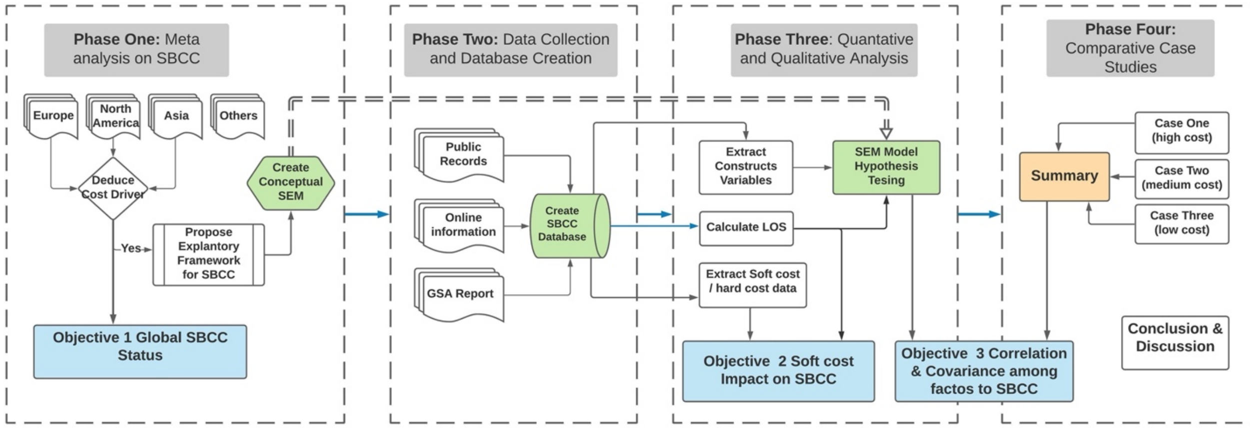


Figure 3.3 Proposed research flow

3.3.1 Phases one: meta-analysis

Phase one is meta-analysis of existing literature on SBCC in comparison to that of conventional buildings. The initial search includes all building types: office, residential, school, higher education, and other commercial buildings. The first aim is to find the normal range of SBCC difference per different building types, the second aim is to determine whether the high construction cost of sustainable building is a global phenomenon. Lastly, to identify the influential factors for the sustainable building construction cost surcharges. literature review papers were exempted from the analysis if they did not provide new empirical evidence on SBCC difference. Similarly, previous studies only focusing on the economic benefits of building green were also exempted since they did not provide evidence of the construction costs.

A total of 36 studies were identified that provided empirical data; 5 studies only included one case and were therefore excluded in the final analysis. Table 3.1 illustrates a comprehensive overview of the main characteristics of cases presented in the literature. Where a source is reported to have more than one case, it means that either more than one building or different versions of the same building were presented in the same study. For example, some studies compare the cost of the real building to its modeled green version. The literature included in Table 3.1 was selected based on the following criteria: (i) the publication addresses the green building construction cost surcharge as the main research topic, (ii) the publication relies on empirical data to draw a conclusion, (iii) the publication specifies the cost data resources, and (iv) the publication calculates the sustainable building construction cost surcharge to conventional buildings in percentage. During the initial search, a relatively large quantity of publications was found to focus on the life cycle cost of green buildings; the research aim was to quantify the economic benefits of sustainable building through savings during the operation stage. Even though those studies addressed important cost issues of sustainable building and had empirical data, the explanation and information of the construction cost could not be extracted from the data presented in the publication; therefore, the researcher excluded those publications in the meta-analysis.

Table 3.1 Overview of Sustainable building construction cost-related publications and data sources

Publication	Country	Year	Case Study #	Type of Building	Area (m^2)	Green Cost Surcharge	Data Source
Xenergy and Sera Architects (2000)	USA	2000	1–3	OF	230–1,432	-0.3%–1.3%	Actual cost data from project team
Kats et al. (2003)	USA	2003	33	SH, OF	NA	-0.66%–6.5%	Survey response (primary architects)

Matthiessen and Morris (2004)	USA	2004	93	AC, LB	NA	No significant difference	Cost estimator database
Steven Winter Associates (GSA) (2004)	USA	2004	2	OF	26,200–30,600	-0.4%–8.2%	Internet search
Bradshaw et al. (2005)	USA	2005	16	RES	400–7,390	-18.33%–8.15%	Literature review and internet search
Kats (2006)	USA	2006	30	SH	NA	0%–6.27%	Actual cost data from project team
Green Building Council Australia (2006)	Australia	2006	8	OF	NA	12–22%	Australian Green Building Council private database
Matthiessen and Morris (2007)	USA	2007	221	AC, LB, SH, OF	NA	No significant difference	Cost estimator database
Davis Langdon (2007)	Australia	2007	3	OF	>15,000	3%–11%	Cost estimator database
Burnett et al. (2008)	China (Hong Kong)	2008	38	OF	NA	0%–3.2%	Construction cost handbook (China & Hong Kong 2006) and cost estimator database
Fullbrook & Woods (2009)	New Zealand	2009	4	AC, HO, SH, OF	3000	1.25%–6.23%	Actual cost data from project team
Houghton et al. (2009)	USA	2009	13	HA	2,800–47,000	0%–5%	Survey response and interview
Kats (2010)	USA	2009	155	RES, HA, HE, SH, LAB, OTHERS	240–200,000	0%–18%	Survey response (primary architects)
Mapp et al. (2011)	USA	2011	10	BANK	281–512	< 2%	Actual cost data from project team

Zhang et al (2011)	China	2011	3	Hotel, OF, RES	33,610–23,710	8.5%–13.9%	Actual cost data from project team
Shrestha and Pushpala (2012)	USA	2012	60	SH		No significant difference	Actual cost data from project team (Clark County School District)
Nyikos et al (2012)	USA	2012	160	ALL	NA	0.66% to 6.5%	Online search
Rehm and Ade (2013)	New Zealand	2013	17	OF	NA	No significant difference	Actual cost data from project team
Building Research Establishment (BRE) (2014)	UK	2014	3	OF	13,800	0%–5.7%	Survey response
NAHB Research Center (2012)	USA	2014	6	RES	232	0.68%–14.65%	Survey response
Kim et al. (2014)	USA	2014	2	RES	270	10.77%	WinEstimator database and 2011 RS Means estimator
Gabay et al. (2014)	Israel	2014	6	OF	1,000–10,000	4.4%–11.6%	Israel Central Bureau of Statistics
Alexeew et al. (2015)	India	2015	4	RES	NA	0.8%–2.8%	Modeled cost
Garcia et al. (2017)	USA	2015	8	RES	95–248.3	13.7%–36.9%	Modeled cost
Dwaikat and Ali (2016)	Global	2016	17	ALL	NA	-0.4%–21%	Literature review
Hwang et al. (2017)	Singapore	2017	363	ALL	NA	4.5%–7%	Survey response (from project design)
Yih Chong et al. (2017)	Malaysia	2017	6	RES	NA	2.2%	Modelled cost
Chegut et al. (2019)	UK	2019	542	ALL	NA	6.5%	The Royal Institution of Chartered Surveyor's BCIS database
Sun et al. (2019)	Taiwan	2019	74	RES	2,085–122,097	-19%–9.3%	Government public

							information websites and architectural professional magazines
Ade and Rehm (2020)	New Zealand	2020	10	RES	NA	3%–5%	Author's own practice data

The sustainable buildings included in the case findings differ in climate condition, function, construction type, location, and source of data. The data sources are listed in Chapter 2 Table 4; they vary widely, from questionnaires (surveys) to actual construction documents. Consequently, it is not appropriate to directly compare the cases against each other. The cases also differ in size and estimated lifetime. In order to neutralize these differences, the cost figures were normalized per unit of area ($\$/m^2$), and then compared in percentages of the additional cost in relation to the conventional building cost described in Chapter 2 Equation 1. The additional sustainable building construction cost includes hard and soft costs described in Chapter 2, conventional building refers to those buildings not certified through any sustainable building certifications.

3.3.2 Phases two: data collection

Phase two is data collection and creating SBCC database. The detailed description of data source, collection procedure and data quantities and quality can be found in Chapter four. The decision of using this data sources was made after more than one year-long data hunting. The researcher has reached out to more than 20 different organizations, professional organization and non-for-profit organization to acquire the cost data, The organizations include United State Green Building Council (USGBC), American Institute of Architects (AIA), Clark construction and others. And no one seems to either have the data or can share the data. So, the researcher decided to reply on the public accessible data. The detailed data collection procedures and data quality are explained in Chapter 4.3.

3.3.3 Phases three: quantitative analysis

For quantitative analysis, regression models and structural equation models are utilized to analysis the data collected in phase two.

<u>*Regression models*</u>

The first regression model is created to study the correlation between level of sustainability (LOC) and SBCC. LOC is measured by the gained LEED score.

$$Y_i = \beta_0 + \beta_1 (SBCC) + \mu_i \qquad \text{Equation 2}$$

Where Y_i is the gained LEED score; SBCC is the total construction cost of LEED certified building, μ_i is the random effect of intercept.

The second regression model is created using Equation 3 through Equation 5, to determine the influential dependent variables to total SBCC (cost components) between hard costs and soft costs. The hypothesis is that hard cost (SC) have greater influence on the variance in the construction cost. The hard cost (HC) is divided into five subcategories based on a commonly used cost estimation adopted by the building and construction industry and used by the *National Building Cost Manual* and RSMeans's *Square Foot Costs Book*. The included subcategories are *Shell (SH), Services (HAVC, fire, etc, plumbing (SE)), Interiors (IN), Structure (ST).* Soft costs included in the study are divided into two categories: design cost (DC) (for architects, engineers and consultants) and management/ inspection cost (IC).

$$SBCC = \beta_0 + \beta_1 (HC) + \beta_2 (SC) + \mu_i \qquad \text{Equation 3}$$

$$SC = DC + IC \qquad \text{Equation 4}$$

$$HC = SH + SE + IN + ST \qquad \text{Equation 5}$$

Using regression models, there are two hypothesis the research wanted to test:

Hypothesis 1a: There is no correlation between the construction cost and the level of sustainability.

Hypothesis 1b: The primary components contributing to the higher cost of sustainable buildings are derived from the hard costs.

Structural Equation Model

In a nutshell, SEM is the merge of two analytic approach: factor analysis and path analysis. Factor analysis had its roots in psychology, Charles Spearman, a British psychologist, is credited with developing the statistical technique known as factor analysis. He proposed that correlations between tests of mental ability could be explained by a common factor representing ability, which is called G factor (Spearman, 1904). In the 1930s, Spearman's one factor concept was criticized by L.L. Thurston, an American psychologist, who was also active in psychometrics, presented work on multiple factor models that include seven primary categorical factors, and together measure the mental ability. In 1969, Karl Gustav Joreskog, a Swedish statistician, introduced confirmatory factor analysis and estimation via maximum likelihood estimation, allowing for testing of hypothesis about the number of factors and how they relate to observed variables (Jöreskog, 1969).

Path analysis and systems of simultaneous equations were developed in genetics, econometrics, and later sociology. Seawall Wright, an American geneticist, known for his work on evolutionary theory, is credited with developing path analysis. His first paper using this method was published in 1918 where he looked at genetic causes related to bone disease in rabbits. Rather than estimating only the correlation between variables, he created path diagrams to that showed presumed causal paths between variables. He compared what the correlations should be if the variables had the presumed relationships to the observed correlations to evaluate his assumptions (Wright, 1934). In the 1930s to 1950s, many economists, such as Haavelmo (1943) and Koopmans worked with systems of simultaneous equations(Koopmans, 1945). Economists also introduced a variety of estimation methods and investigated identification issues. later in the 1960s, path analysis was introduced to social science research by Blalock and Duncan (1966).

The two approaches were merged in the early 1970s. (Hauser & Goldberger, 1971)worked on including unobservable into path models, which later on be defined as latent variables. Jöreskog (1970) developed a general model for fitting systems of linear equations and for including latent variables. He also developed the method for fitting these models using maximum likelihood estimation and created the program LISREL, one of the most used computer program for SEM research. Much work has been done since then in to extend these models, to evaluate identification to test model fit, and more, and it has been employed in many fields and disciplines. SEM is not just an estimation method for a particular model, it is a powerful, multivariate technique found increasingly in scientific investigations. Some may say SEM is a way of thinking, design research and a way of estimating. It differs from other modeling approaches as it tests the direct and indirect effects on presumed causal relationships (Fan et al., 2016), and it can test multiple hypotheses simultaneously. SEM has five advantages over traditional regression and factor analysis techniques: (1) *reliability*: explicit assessment of measurement error; (2) *complexity*: testing of complex patterns of relations, including a multitude of hypotheses simultaneously; (3) *multi-dimensional*: estimation of latent variables via observed variables; and (4) *validity*: model testing where a structure can be imposed and assessed per data fit. SEM combines factor analysis and multiple regressions with two components: a measurement model and a structure model. Measurement models are powerful in that they can specify how measured proposed *constructs* and *variables* come together to represent *concepts* and *outcomes*. Structure models estimate how *constructs* and *variables* are related to one another.

SEM is often drawn as Path Diagram to demonstrating the causal relation between variables. Before the discussion of included in variables and hypothesized causal path, it is important to clarify the terminologies and symbols used in SEM diagram. Table 3.2 is the explanation of variables used in SEM, and Table 3.3 lists common symbols used in SEM.

Table 3.2 Terminologies used in SEM

Observed variables	variables that are included in the data set. They are represented by rectangles. In the proposed diagram, B1 through B13 are observed variables.
Latent variables	unobserved variables we wish to comprehend. They can be thought of as a composite score of other variables. They are represented by ovals. In the proposed diagram, project team characteristics and project characteristics are observed variables.
Paths	direct the relationships between variables. Estimated path coefficients are analogous to regression coefficients. They are represented by straight arrows.
Covariance	specify that two latent variables or error terms covary. They are represented by curved arrows.
Exogenous variables	are determined outside the system of equations. There are no paths pointing to it. The variables B1 through B13 are exogenous.
Endogenous variables	are determined by the system of equations. At lease one path points to it. The variables such as "project team characteristics" is endogenous.
Observed Exogenous	a variable in a dataset that is treated as endogenous in the model
Latent Endogenous	an unobserved variable that is treated as endogenous in the model

Table 3.3 Notation and symbols

Notation	**Symbol**
Observed Endogenous	y
Observed Exogenous:	x
Latent Endogenous	η
Latent Exogenous	ε

Error of observed endogenous	$\mathrm{e.y}$
Error of latent endogenous	$\mathrm{e.}\eta$
All endogenous	$\mathrm{Y = y}\ \eta$
All exogenous	$\mathrm{X = x}\ \eta$
All errors	$= \mathrm{e.y\ e.}\eta$

$$Y = \alpha + \beta_1 Y + \beta_2 X + \zeta$$

Where the β_1 and β_2 are coefficients of observed endogenous and observed endogenous. α is the intercepts. ζ represent the error.

As for the required sample size, ratio of observations to free parameters from 5:1 up to 20:1 have been proposed in the previous studies. In this dissertation, there are 11 observed variables, total 113 sample data sets (GSA LEED certified projects) are used for SEM, the ratio is around 10:1.

Figure 3.4 illustrates the conceptual SEM model proposed in this dissertation, and Table Table 3.4 presents the short description of the variables. How those variables (B1-B13) are extracted from meta-analysis is explained in Chapter 4, and how variables are measured is explained in Chapter 5.

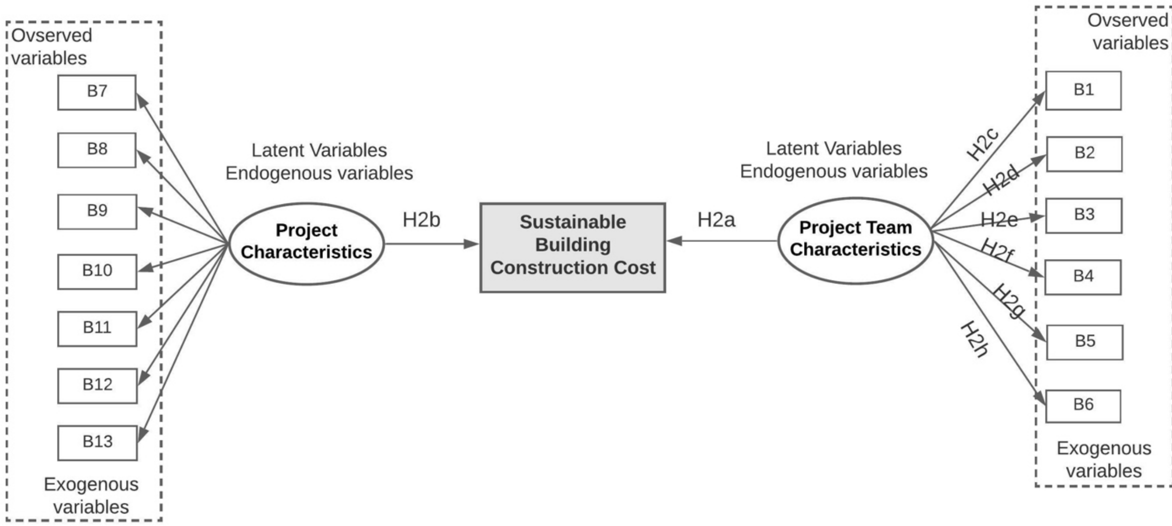


Figure 3.4 Proposed Conceptual SEM diagram

Table 3.4 SEM constructs and factors

Project Team characteristic		**Project characteristic**	
B1	Procurement	B7	Level of sustainability
B2	Skill	B8	Building types
B3	Experience	B9	Construction types
B4	Communication	B10	Technical complexity
B5	Collaboration	B11	Project location
B6	Motivation to innovate	B12	Project scale
		B13	Material availability

A software called STATA is used for SEM analysis. Since the proposed SEM is a continuous outcome models, therefore the function in STATA SEM is used for analysis. To respond to the three objectives outlined in Chapter 1, using SEM there are eight hypotheses to be tested in this study, H2a through H2h. (listed in Chapter 5)

3.3.4 Phases four: case studies and ground truth the findings

After understanding the correlation and covariance among the project characteristic variables and project team variables to SBCC, the final step is to gain a deeper understanding how the variables influence the final construction cost of sustainable buildings, and through what mechanisms those influential project team characteristics imposing the impact on construction cost. Three cases are selected for in-depth analysis from the SBCC database: one from high cost bucket, one from median cost bucket, one from the low cost bucket (cost is measured by $/SF). All three cases have more detailed project description and statement documenting the project and project team characteristics, such as procurement process, team collaboration methods, frequency and format of communications among others.

3.4 Chapter Summary

This chapter outlines the research and design selection and a data analysis approach for this dissertation, it also presents the background and justification for this research design. This research uses the programmatic approach and assumption. The research methods employed for this dissertation is a combination of quantitative and qualitative approach, the research techniques utilized for this dissertation include meta-analysis, regression model analysis, structure equation model analysis, and case studies. The research process includes four phases: Phase one – meta-analysis, Phase two – data collection, Phase three – statistical analysis, Phase four – case studies. In the following chapter, Chapter 4 and Chapter 5. The findings from the research phases are presented.

Chapter 4 Global Status of Sustainable Building Construction Cost

Chapter 4 discusses Phase one research activities and findings. Phase one of this research is meta-analysis. First the findings of additional sustainable building construction cost compared to conventional buildings at global scale are summarized and discussed. Then the cost factors related to the additional cost are extracted from meta-analysis and potential mechanism of those cost factors are explained as well. Chapter 4 sets a foundation for the Phase 2 data collection.

4.1 Meta-Analysis Results: Global Status of Sustainable Building Construction Cost in Comparison to Conventional Building

As pointed out from literature review results summarized in Chapter 2, the growth of research in sustainable building constructions cost is limited in the past several decades. And the due to the lack of quantitative data, there is no meta-analysis conducted on the topic of sustainable building construction cost at global scale.

In phase one research, this meta-analysis surveyed the existing body of literature to aggregate the findings of empirical evidences that address the sustainable building construction cost (SBCC), and to comparatively analyze the differences across building types, continents, and construction cost data sources, to gain an understanding of the cost drivers that have an influence on SBCC. To understand how SBCC different from the construction cost of conventional building (CCCB), the measurement introduced in Chapter 2.2, sustainable building construction cost surcharge (SCS) is used to measure the difference between conventional building construction cost and sustainable building (refer to Eq.1).

SCS = additional SBCCs/conventional building construction cost (Eq. 6)

Total **31 s**tudies including more than **1,320** buildings from 11 countries are included in the meta-analysis. Primary cost factors are extracted from the meta-analysis findings to create the proposed explanatory framework to explain the SBCC. And those extracted cost drivers are used to create the conceptual structural equation model (SEM), SEM results are explained in the following chapter, Chapter 5.

4.1.1 Difference of SCS among building types

Figure 4.1 illustrates that among the different building types, school (K-12) buildings have the highest mean (average) SCS, at 18%, which is much higher than all other building types. The office buildings have the second highest mean SCS, at 6%. The residential building has third highest mean SCS at 4%. And the academic buildings (higher education buildings and other learning facilities) do not show a significant difference between sustainable building construction cost and conventional building construction cost. When looking into the median SCS, residential buildings, and school buildings have the same median SCS of 4%. Office buildings has highest median SCS of 5%, and Adamic buildings has the lowest SCS of 0%.

In addition, most of the school, office, and residential building costs are above the mean, and other commercial building types have an even split between cases with a SCS below and above the median. These findings are aligned with previous studies where the *building type* was found to be a significant factor affecting the cost surcharge (AIA, 2020). However, the mechanism how the building type has impact on the construction cost of sustainable building have not been clearly explained. Currently, in the United States, school buildings are leading the effort in advancing sustainable building. According to a 2019 National New Building Institute report, educational buildings represented the largest portion of net zero energy projects, at 34% (NNBI, 2019). Within the education buildings, K-12 schools account 54%, higher-education buildings accounts 32% and general education building is the rest 14%. School buildings as a special type of public building has a significant role in promoting and educating public about sustainable building, the high SCS of those net zero school buildings can be a contributor to the public's perception of sustainable buildings as being expensive to build.

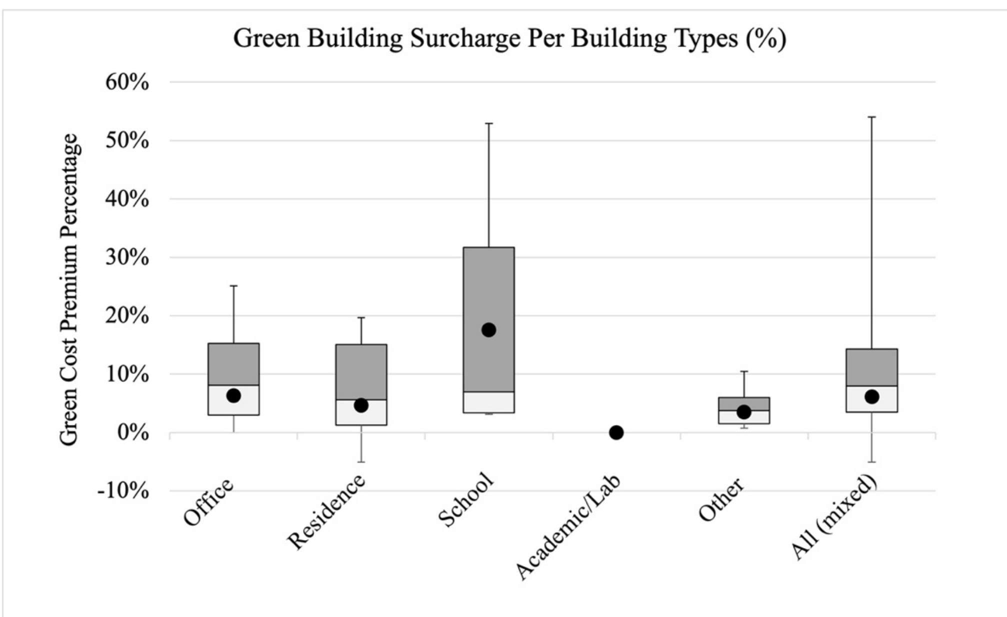


Figure 4.1 Sustainable building construction cost comparison per building types

Regardless the difference, overall, based on empirical data collected from the previous studies globally, the mean of SCS is **6%** for all building types combined together. In addition, the distribution between the projects above and below the mean are equal. Hence, 7% can potentially be used as a benchmark to describe the SCS across building types and regions.

4.1.2 Difference of SCS per continents

Figure 4.2 shows that the median value of SCS in all regions is less than 5%, with Asia having the lowest value at 2% and North America having the highest value at 6%. Even though Asia has the lowest median value, as illustrated in Figure 4.2, the majority of projects are actually in the higher sustainable surcharge range (> 5%), that is represented by the longer upper grey box. When looking at the mean (average) SCS, Europe has the lowest value of 3%, followed up Asia (5%), Oceania (6%) and North America has the highest mean, at 7%. The North America also has the largest SBCC variation among buildings, from -18.33% to 46%, and Europe has the smallest SBCCS variation, from 0% to 6.5%. The wide range of cost differences in the North America is an indication of lower level of maturity of sustainable building practice compared to Europe, and higher labor/material cost variation compared to Asia. Overall North American market is a great region to conduct further investigation due to its high mean SCS and large cost variation. At majority case projects included in North American are from the United Sates, therefore focusing on cases from the United States is the logic step.

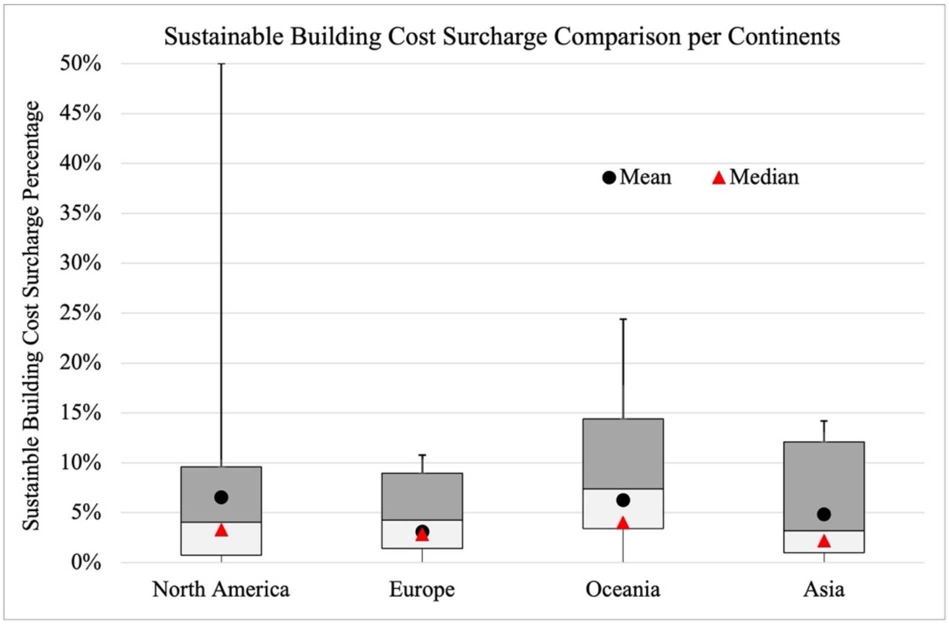


Figure 4.2 Sustainable cost surcharge comparison across continents

4.1.3 Difference of SCS per LEED certification levels

Based on the existing literature, within the same building types, level of sustainability may play a role in the range of cost premiums seen in the market. In general, LEED certified building's base construction costs were found to be within the same overall cost ranges as that of conventional buildings. Then added soft cost of LEED certified building was mainly due to the administrative work and outside consultant fee, such as LEED certification fee (Mapp et al., 2011). As for other LEED certification level, there have been different SCS associated with different certification levels. For example, a U.S. General Service Administration commissioned study showed LEED Silver building require 2% premium, LEED Gold building can add 7% to the construction cost (Steven Winter Associates, Inc, 2004). A more recent study showed LEED Gold and Platinum certified buildings' additional construction cost were found to be 7.43% and 9.43% respectively (Uğur & Leblebici, 2018). Not all included studies have conducted breakdown information of the level of sustainability of studied buildings, hence, there is no summary can be concluded from the meta-analysis on whether level of sustainability actually is associated with the construction cost. So, the breakdown analysis will be included in this dissertation study.

4.1.4 Difference of SCS per construction cost data sources

Among the included 31 studies, 22 studies (1692 buildings) used actual building data, and the remaining 9 studies (77 buildings) used hypothetical data. Figure 4.3 illustrates the SCS statistics of the actual buildings and hypothetical buildings. Two conclusions can be drawn. *First*, the average SCS for cases using the actual building cost is 6%, which is slightly higher than that of hypothetical buildings. However, the actual buildings' median SCS is lower than that of hypothetical buildings, by 2%. This indicates that the majority of the SCS of the actual building cost is higher than the hypothetical SCS; this can be explained by the risk and uncertainties that occur during the construction. *Second*, actual buildings have a much larger cost variation, from -5% to 46%, which is associated with the uncertainty and cost overrun during the actual construction process. Cost overrun is generally a symptom of inadequate planning and poor management (AIA, 2020). It was found that green building projects have higher cost overruns than conventional buildings and more costly than conventional building projects (AIA, 2020). Using hypothetical buildings and modeled construction costs might be sufficient to help the public gain an understanding of the average or median green cost surcharge; however, to account for uncertainty in a real project and ensure the actual construction cost will be within the budget, using the actual project cost data is critical, since the modeled cost cannot provide an accurate picture of the challenges and uncertainties that occur during construction.

Figure 4.3 Green building construction cost surcharge comparison between cost estimation methods

As demonstrated in Table 4.1, there is no standard process for how the cost data are collected in those studies. Only 21% of studies were able to obtain the actual construction cost data and documents from the project team, and 25% of studies relied on survey or questionnaire responses from the project team members (architect, interior designers, engineers) and clients/developers. Some studies use public accessible data rather than contacting project teams. For example, Chegut et al., (2019) used the Royal Institution of Chartered Surveyors' BCIS database, Sun et al., (2019) used the Taiwanese government's public information websites, and Gabay et al., (2014) used data from Israel's Central Bureau of Statistics.

Table 4.1 Methods and cost estimation methods in prior studies

	Method	# Studies
Actual building	Survey responses from professionals (cost estimators, contractors, architects	5
	Actual cost information from project team (client, architects, engineers, cost estimators)	8
	Cost estimator database (Davis Langdon Database)	4
	Publicly available data (governmental databases or others)	4
	USGBC data (not accessible to the public)	1
	Author's own data from practice	1
Hypothetical building	Case studies of real projects using modeled cost and hypothetical green scenarios	4
	Model green building costs of actual building based on green specs	2
	Model green building costs of theoretical building based on design requirements	1
	Unknown	1

4.1.5 Difference of SCS between studies by industry experts and academic researchers

There are noticeable differences between studies published by academic researchers and industry experts. As illustrated in Figure 4.4, 65% of the studies were conducted by industry experts and published by trade organizations, professional associations, or green building certification organizations. The data collection and research methods of these studies were typically not well defined or explained in the publications. Furthermore, the studies by industry experts are older, with most of the studies published before 2010 and only three studies published after 2010. On the contrary, the majority of the academic publications are relatively recent, after 2010 (Dwaikat & Ali, 2016), and only one study was conducted and published before 2010. The mean SCS from the academic research is 10.2%, which is much higher than that of the industry-associated published studies, at 3.06%. It is understandable that in the early period, the primary cost data resources were gathered by industry experts, particularly professionals working in the green building field, and the research and reports based on empirical data demonstrating the economic feasibility certainly has helped promote building green.

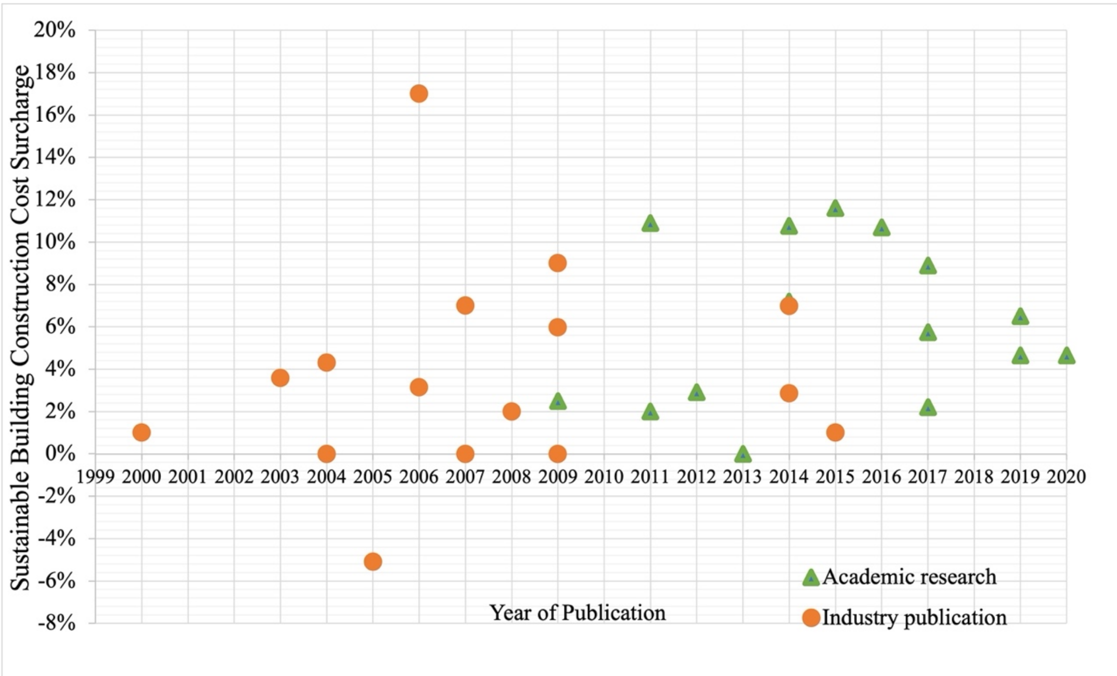


Figure 4.4 Comparison of studies published by academic researchers and industry experts

4.1.6 Summary of meta-analysis findings

Based on the identified construction cost difference between sustainable buildings and conventional buildings from the meta-analysis results, three conclusions can be made. First, it appears that the higher level of "green-ness" is potentially associated with the higher additional construction cost at global scale. But the cost surcharge is smaller than the perceived value, mean 6%, and median less than 5%. Second, the data sources used for those studies had influence on the analysis results, the studies using the actual building have higher mean SCS cost of 6% as compared to that of speculative building of 4%. And the cost variance is much larger in actual buildings as compared to speculative buildings. The diverse collection procedure and data sources used in those studies is a clear indication of standardization of data collection and validity is critical to reach the consensus around sustainable building construction cost. Third, there is clear division of the results depending on who conduct the studies for what purpose. Early studies conducted by practitioners showed small SCS while more recent studies from academic researchers have higher SCS. The potential causes for such differences can be related to study methods in addition to the data used. The ambiguity and sometime conflicting results of the previous studies have been fed into the perception of sustainable buildings' high construction cost.

In the following sections, the cost factors for additional construction cost of sustainable building extracted from meta-analysis are explained. The cost factors will be used in structural equation model to understand the causal relation between those factors and total construction costs.

4.2 Cost Influential Factors of SBCC Derived from Meta-Analysis

The factors that affect construction cost identified in previous research can be generally categorized into three categories, project specific characteristics (e.g. building size and location), project team characteristics (e.g the experience of design firm), and external characteristics (e.g. climate condition). This study focuses on the first two characteristics. The criteria author used to identify the characteristics from meta-analysis are: (1) data regarding the characteristics can be collected for the studied cases, (2) the characteristics at least identified in five previous studies. Some characteristics have been mentioned in many studies but difficult to be collected for large number of the case projects were excluded from this study. For example, it is difficult to collect data on the labor productivity and project manager's working relationship with others for 175 cases projects that were included in this study.

As illustrated in Figure 4.5, six project team characteristics were identified and seven project characteristics were identified.

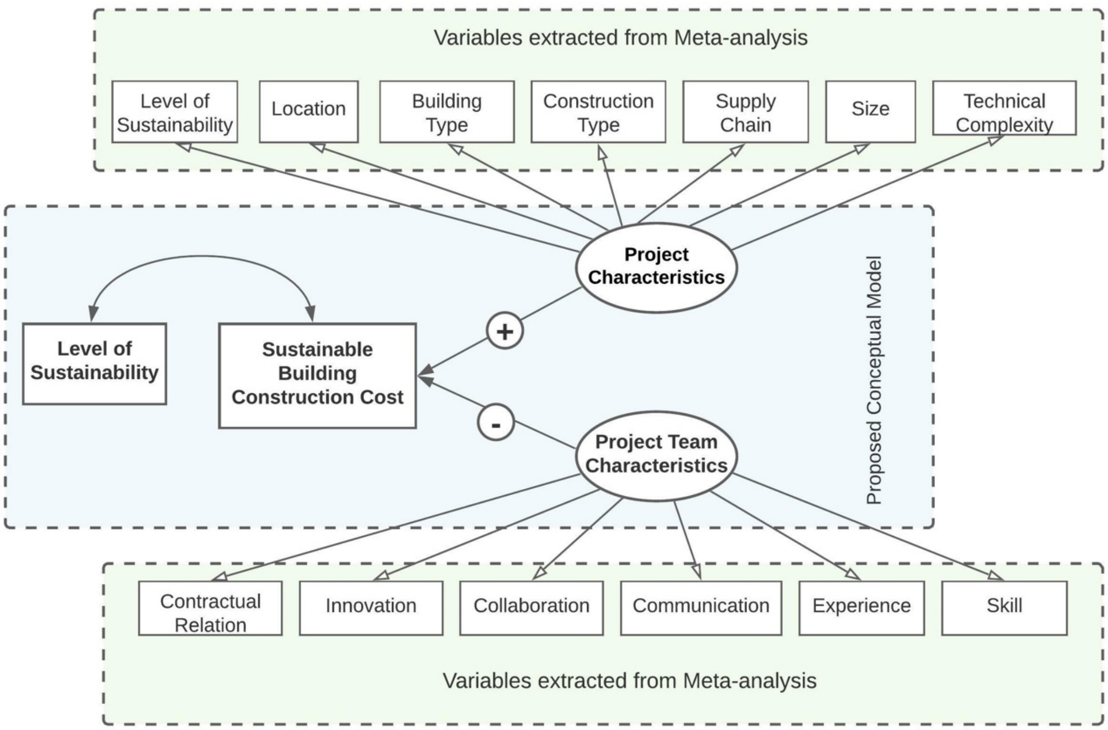


Figure 4.5 Influencing cost variables extracted from meta-analysis

4.2.1 Project characteristics variables

Technical complexity

Technical complexity is commonly speculated factors and drivers driving the high sustainable building construction cost. Complicate building system's direct impact on the construction cost are often reflected in higher material, labor and equipment cost. Complex building system also indirectly impact the construction cost through the demand for more skilled design team, contractors and potential longer design/coordination time and construction schedule.

Supply chain maturity

Supply chain maturity may affect the availability of building materials and components but does not contribute directly to the total construction cost. A mature supply chain can improve efficiency and productivity and reduce overall costs (Ofori, 2000). and the supply chain's maturity is closely related to the availability, manufacturing, and transportation method of the sustainable building materials. The higher cost of sustainable materials arises in part from the immaturity of the supply chain, which leads to a scarcity of sustainable materials and consequently an increase in the construction costs (AIA 2020). In developing countries where the green building market is still new, certified green products or components have to be imported, which also adds additional costs. Zhang et al (2011) stated the cost of sustainable materials is 3% to 4% higher than that of conventional building materials. (Hwang & Tan, 2012) showed how compressed wheatboard costs about 10 times more than ordinary plywood. (Amiril et al., 2017) also pointed out how the shortage of sustainable building materials has in fact been one of the barriers to promoting sustainable building.

Construction types and project types

Regarding the construction methods and types, sustainable construction methods, such as prefabrication or modular construction, can reduce construction waste (Tumminia et al., 2018). However, prefabrication housing was found to receive less demand due to its high cost and current cheap labor rate (Russ et al., 2018). In addition, the higher prefabricated building assembly cost was identified as one of the main reasons for a higher SCS (Mao et al., 2016). Moreover, the construction methods or logistics for sustainable buildings are different as well. (Mao et al., 2016) pointed out that in a traditional construction practice, the tower crane enters the site once every nine months; in contrast, in some sustainable construction sites, a tower crane enters the site twice every eight months. Consequently, the costs related to the tower crane contribute to the green cost surcharge (Home Innovation Research labs, 2012).

Structural systems and material selection also play significant roles in determining the final construction cost. For example, Gan et al (2017) evaluated the impact of the choice of construction materials and structural form of high-rise buildings. Their study showed the steel building has the highest construction cost followed by the reinforce concrete buildings. Meanwhile the steel building also produced the most embodied carbon, that made the steel buildings less sustainable from whole building life cycle perspective. Another study showed the use of wood as primary structure material for nonresidential building could lead to the cost reduction, however there are still policy and regulation obstacle exists for adopting wood as a primary structure materials for high-rise building, such obstacle can lead to cost increase (Gosselin et al. 2015).

Project location and size

The building construction cost is affected by a combination of different localized variables, and therefore they are sensitive to geographic variations (Migliaccio et al., 2013). The physical characteristics such as project location, project size, accessibility and topography are all influential variables (Akintoye, 2000). Location can have a direct impact on labor availability, equipment availability, local taxes, inflation and other weather and climate condition (Migliaccio et al., 2013). The geographical location also has a considerable influence on the likely financial implication of construction projects, it has been recognized by several researchers as a key cost drivers at global scale (Stoy et al., 2008) (Dursun & Stoy, 2011). At country level, (Dursun & Stoy, 2011) found the relation between construction cost and location of a building is fundamental for the determination of construction duration.

4.2.2 Project team characteristics variables

Procurement

Procurement method has been found influential to team culture and team organization in some previous studies (Y.-M. Cheng, 2014). Procurement method in building and construction industry has been defined as a process of selecting and hiring a team for the design and construction of a project (El Wardani et al., 2006). The method of procurement is critical as it affects how a project would be delivered and financed (Hwang et al., 2017), it also has impact on trust among stakeholders and openness and communication among team members (Shen et al., 2017), and influential to risk management in construction projects (Osipova & Eriksson, 2011).

The selection of the appropriate procurement method for Design-Bid-Building(DBB) or Design-Build (DB) projects is an important decision for owners because it leads to the selection of the project team. Sanvido et al., (1992) found that the selection of the right team with effective organization is essential to ensure a successful project delivery without cost overrun and schedule overrun. Since then, the procurement options were found

Skill and Experience

Project design team play an important role as their work involves from inception to completion of a project. (Chan & Kumaraswamy, 1997) considered design team-related cost influential factors consists of design team skill and design team experience. The availability of quality human resources plays important role in success of building projects. Expected construction progress can be achieved only through the attainment of effective man-hour effort and the meeting of scheduled milestone dates. The shortage of skilled personnel and related high labor cost and fluctuation of labor productivity have been identified as the major cost drivers in previous studies (Creedy & Kalb, 2005) (Naoum, 2016)

Collaboration and communication

Collaboration is often referred to as "working together" and can be reflected in different forms (Hughes et al., 2012) and relate to the procurement type. The definition adopted in this study was derived from a comprehensive review conducted in 2012, which is closely related to partnering (Hughes et al., 2012). Collaboration of a building project refers to the team effort by all participants, at the early design stages, the participants are project manager, architects, engineers, consultants, and owners, potentially construction managers. The project manager play a key role in success of a project through management of schedule and budget (Belassi & Tukel, 1996). In the previous study of green building cost, the intensive up-front collaboration during the design stages were found necessary to support the technology application. For example, in a multi-family apartment building (in New York City) project, the project team claim that the use of a single down-sized boiler for heat and hot water can be considered as an innovative energy saving technology and needed intensive collaboration (Bradshaw et al., 2005).

Innovation

The construction industry is often compared unfavorably with the manufacturing sector in its ability to generate technical innovation (Hardie & Newell, 2011). However, innovation is critical to long-term success in the construction industry. Within the construction industry, the definition provided by Slaughter (1998) is broadly accepted by academics and practitioners.

Innovations is the actual use of a nontrivial change and improvement in a process, product, or system that is novel to the institution developing the change.

There is a wide range of innovation in construction sector from all stakeholders, that including clients, designers, suppliers, contractors, end users, vendors and distributors, certification bodies, and others. Six primary factors that hindering or promoting the innovation in construction are identified by previous studies: (i) procurement system/ method (Walker, 2003), (ii) Technical competence of team is also a significant enabler for construction innovation (Pries & Janszen, 1995), (iii) project resources and organization resources and culture (Chandler et al., 2000), (v) regulation and standards (Meng & Brown, 2018), (vi) relation within the project team (Meng & Brown, 2018). In general, project-specific factors that are influential to innovation are less studied. Among the limited studies, the focus has been on contractors' input. For example, Slaughter (1998) found the contractor's innovative approach to overlap the different construction phases were beneficial to shorten the construction schedule and reduce cost overrun.

4.3 Chapter Summary

Chapter 4 explains findings from meta-analysis. Even though the meta-analysis results showed there is construction cost difference between sustainable building and conventional building, however, the difference of 6% (mean) is smaller than what has been perceived. Moreover, after diving deeper, the untransparent and unstandardized data collection and sources method made the findings less robust and cast more doubts on its reliability. In addition, the clear division between findings between academic research and industry report demonstrate the clear needs for further examination. The most important aspect of Chapter 4 is that critical cost factors were extracted from the meta-analysis and organized into two categories: project characteristics and project team characteristic. Those factors are used as a contextual foundation to generate Structural Equation Model (SEM).

Chapter 5 Sustainable Building Data Collection Procedure and Data Descriptive Statistics

Chapter 5 discusses Phase two research activities and findings. Phase two research task is data collection and creating sustainable building construction cost (SBCC) database. SBCC was created with three types of data: construction cost data, project team characteristic, and project characteristic data. The cost data was obtained first, then the project and project team characteristic data were collected accordingly. The main resource of cost data is General Services Administration (GSA) record and GSA website (for project budget). For the project characteristics data were extracted from variety documents found online, includes project website, project statement and case studies done by GSA or researchers. The project team characteristics data were drawn from variety online sources, including project reports, commissioned case studies, published journal paper and phone interview with project team members. For example, Aspinall Courthouse building is the GSA's first net zero historical renovation project, certified as LEED Platinum. National Renewable Energy Laboratory together with GSA team produced a very detailed 37 pages case study report documenting the design and construction process of how the project achieved this high goal. Project team members were interviewed to draw the lessons learned and suggestion on further process. Team member's interview quote were extracted and included in SBCC database. After explaining the data source and collection process, descriptive statistics are offered for each data types as well.

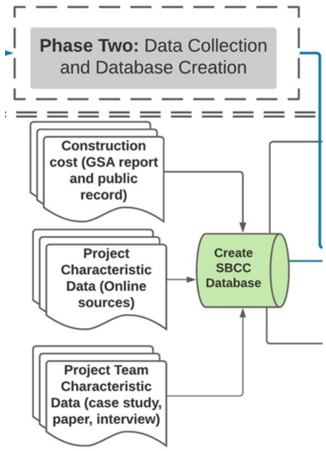


Figure 5.1 Research phase two diagram

5.1 Construction Cost Database Collection

As a result of a 2006 GSA evaluation of sustainable building rating systems, the administrator concluded that LEED® remains the most credible rating system available to meet GSA's needs. Since then, GSA has increased its minimum requirement for new construction and substantial renovations of federally owned facilities to LEED certified (*LEED Building Information*, n.d.). According to the Freedom of Information Act (FOIA), the researcher requested information of the construction costs of all LEED-certified government buildings on March 15, 2021. Through email correspondence with GSA, the researcher has further clarified the FOIA request on March 25, March 29, and then again on April 5. GSA agreed to provide a report of building-specific construction costs of all **175** GSA-owned LEED-certified buildings that were on record as of March 31, 2021 (refer to Appendix for GSA agreement). On May 12, 2021, GSA provided the report with the agreed-upon information.

As illustrated in Figure 5.2, among the 175 buildings provided by GSA, 17 projects do not have cost information, hence they were excluded, that left 158 projects. To verify the LEED certification level of case projects, researcher cross reference the 158 projects with the USGBC online project directories, 45 projects are registered with USGBC, but have not received the final certification, therefore, they were excluded from the database. The cross-reference resulted 113 projects.

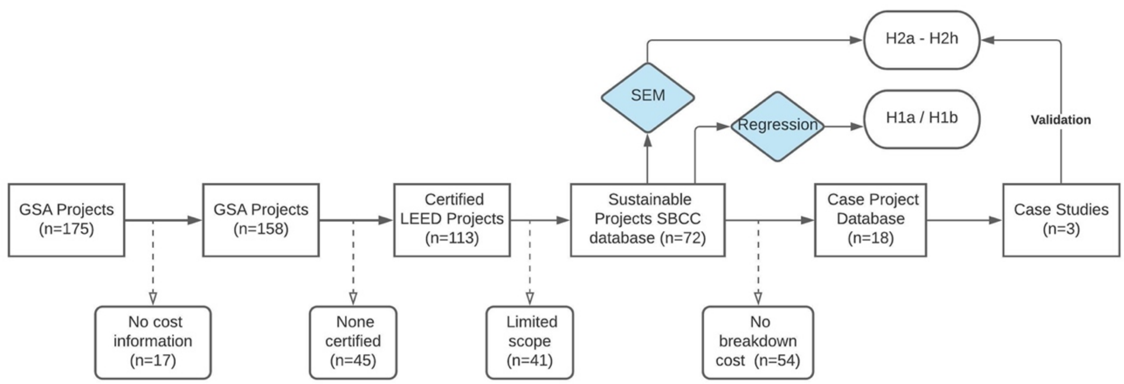


Figure 5.2 Data collection flow

After the preliminary examination of the 113 projects' cost, 41 projects were excluded due to the limited scope of work, and rest 72 projects were included to create SBCC database, (refer to section, 5.2.1.) Accordingly, the project and project team characteristic data were collected from the 53 projects to create a complete SBCC database, and then were used to study the relation between the level of sustainability and construction cost using regression model. SBCC was also used for Structural Equation Model (SEM) analysis.

The construction cost data provided by GSA does not have a detailed cost breakdown for major building components and systems. The researcher was able to find and download the budgeted cost breakdown per major work performed for each major building systems from the GSA website for 18 projects (i.e. mechanical system, structure system). Figure 5.3 represent the detailed cost breakdown per building systems. Lastly, from the 18 projects, three case projects representing low, media and high cost were selected for further studies to understand and validate the analysis results from SEM model.

Major Work Items	
Exterior Construction	$8,470,000
Interior Construction	34,176,000
Electrical Replacement	16,120,000
Fire protection and Alarm Upgrades	6,010,000
HVAC Replacement	42,486,000
Plumbing Replacement	6,784,000
Special Construction/Security Upgrades	7,319,000
Demolition and Abatement	11,269,000
Site Work	1,540,000
Total ECC	**$ 134,174,000**

Figure 5.3 Hard cost breakdown

5.2 Construction Cost Database Descriptive Statistics

5.2.1 Project cost range

Figure 5.4 shows in SBCC database created for this research, 37% buildings (dark grey bar) construction cost are less than $\$50/ft^2$. Such low cost is related to the limited scope of work in those projects. Large number of the renovation projects did not involve major building systems upgrades or renovation, rather, the limited work included were mainly cosmetic, such as repaint and minor repair. Only a few projects in this category did have a few buildings system upgrades (i.e. fire alarm system). Since the limited scope of work would not be sufficiently reflect the technical complexity of sustainable building, therefore, those projects were excluded from the further analysis.

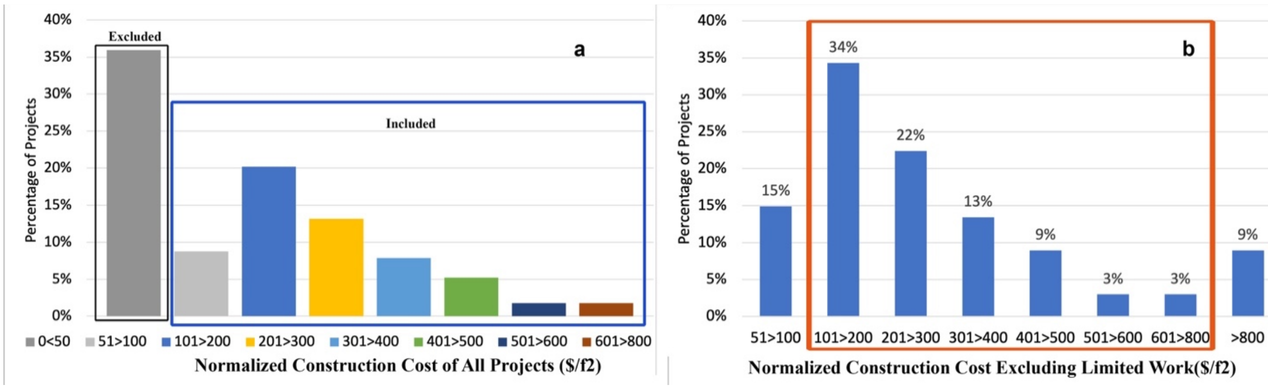


Figure 5.4 Construction cost distribution of all projects

After excluding those limited work, as illustrated in the right side of Figure 5.4b, overall, 84% of the projects fall under \$101–\$800/ft^2. Among the renovation projects included, the projects had at least four primary building systems completely renovated or replaced. In many of the renovation projects, the only system left untouched was the primary structure, which includes the foundation, columns, and floor. The primary structure construction cost is less than 20% of the total construction cost for commercial buildings.

Based on recent data (2021),[1] the construction cost of a new mid-rise office building in the United States is around \$562/ft^2; for high-rise buildings, the cost is \$660/ft^2. If the cost of the primary structure is discounted (-20%), then the average construction cost of major renovation projects is \$450/ft^2 and \$528/ft^2, for mid-rise and high-rise offices,

[1] https://ccorpinsights.com/costs-per-square-foot/

respectfully. Therefore, according to this data, the GSA LEED buildings' construction cost is comparable to the conventional commercial office buildings' cost.

Within this range (\$101-\$800/ft^2), the largest percentage of normalized cost is \$101-\$200, 34%, one project falls this bucket was selected for case study (refer to Chapter 7), to present the lower cost buildings. The second largest group of buildings is at cost range \$201-\$300, 22%, that represent the mean and median cost (refer to Chapter 7). One project from this bucket was selected for case study as well. The third largest group is at cost range \$301-\$400, one project was selected from this group to represent high-cost building (refer to Chapter 7).

Very high-cost buildings (>\$800/ft^2) count for 9%. After reviewing the information of those projects, the researcher determined those projects are very specific, do not represent a general condition of GSA project, let alone normal sustainable buildings. For instance, four port of entry building complexes cost more than \$900/ft^2. Unlike regular administrative buildings, port of entry buildings has higher security requirements and other specific programs and space requirements related to function of port of entry. Those programmatic requirements are not applicable to any other normal administrative buildings, and the design and technologies employed in those buildings are often not applicable to other buildings, therefore the researcher did not further explore those projects.

5.2.2 Cost variance per geographic location

As for the cost difference per geographical location, as showed in Figure 5.5, location 7 (CA, AZ, AL) has the highest average construction cost and largest cost variance, it is mainly due to the high construction cost in several major cities in California, such as San Francisco and Los Angeles. Location 2 (Mid-Atlantic region) has the second highest average construction cost, and it is understandably related to the high construction cost in major metropolitan cities in this region, such as Washington DC. Location 6 (CO, UT) has the lowest average construction cost followed by Location 5 (IL, IN, OH, MN). Two interesting geographical locations merged from these preliminary results that are opposite to the researcher's original assumption**:** Location 2 and Location 1.

Even though location 2 (DC-MD-VA) has the second highest average construction cost, however, the average price is still comparable to conventional buildings ($225/ft^2). In addition, the projects in those states has the least cost variance across the building types, function, size and age. Such finding deviates from the common perception around the construction in this Washington DC metropolitan region is typical more expensive with higher cost variance.

Location 1 (WA, OR) has a symmetrical distributed the box plot diagram, such normal distribution is an indication that the market in this region is relatively mature compared to other regions, regarding the skilled project team, availability of materials and potentially supply chain maturity in this region. Another possible reason for such normal distribution is that the projects in location 1 are very similar in terms of type, complexity and scope.

Both location 1 and 2 have the mean average construction cost that are comparable to the convention buildings, even lower than similar projects. For instance, in Washington DC, the average construction cost for a new mid-rise office building is $562/ft^2, and for major renovation is $450/ft^2. In the SBCC database, the average construction cost of projects in Washington DC is $180/ft^2, and all projects are major renovations. The potential explanations to the actual competitive and even lower construction cost of sustainable buildings is that those two regions may have relatively high skilled the project team who can execute complicate sustainable project, In addition, the relative mature supply chain in those regions can provide reasonable price of the building materials. The assumed explanatory factors are further examined using SEM.

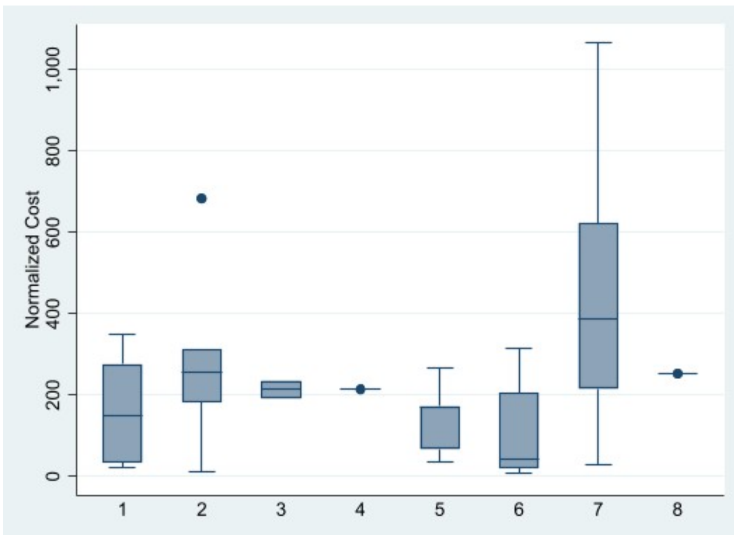


Figure 5.5 Cost variance per location

1	OR-WA	5	IL-IN-OH-MN
2	DC-MD-VA	6	UT-CO
3	NY-NJ--MA-CT-PA	7	CA-AZ-AL
4	TX	8	FL

5.2.3 Cost variance per scope of work

It was not surprised that the new construction project has higher construction cost than that of renovated buildings, for both limited renovation and full renovation. As illustrated in Figure 5.6, the average construction cost of new GSA LEED building is at \$425/ft^2, fully renovated building has average cost of \$204/ft^2. Two findings are worthy to mention that differ from common perceptions. First, the new construction has the largest cost variances among projects, with the higher cost building (the portion above the median line) varies more than lower cost building (the portion below the median line). The second finding, the box and whisker chart of fully renovation project has a symmetric configuration distribution with couple extreme outliners. Such symmetrical normal distribution is different from the typical positive skewed distribution that represent fewer very high-cost project.

In common perception, the renovation project can carry more uncertainty than new construction due to the incomplete information of existing building condition. Also, the renovation projects are often seen as challenging because of the site constrains and technology constraints. The uncertainty and risk often leads cost overrun and large cost variance among projects, consequently, the positive skewed distribution can be observed in renovation projects. However, this is not the case in GSA LEED buildings included in SBCC database. Results showed in Figure 5.6 suggest the uncertainty and risk can be well managed in renovation projects, it also suggest common practice can be derived from the success of GSA LEED renovation projects. Such findings provide the clue for the selection of case projects for in-depth study.

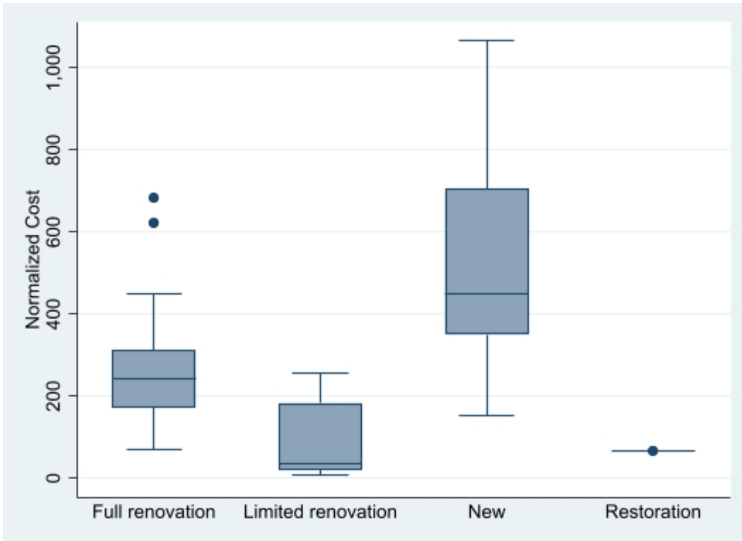


Figure 5.6 Cost variance per construction types

5.2.4 Cost variance per building type

Figure 5.7 shows the cost comparison among different building types. Ports of entry has the highest average construction cost and courthouse has the largest cost variances. Compared to other federal building, port of entry has more speciality functions, and often has customized high-profile design that embodied the symbolic meaning of entry of the country. Such high-profile design was often reflected on speciality construction and related higher cost, such as double skin façade, large overhanging PV panel covered roof (refer to Figure 5.8 San Ysidro Land Port roof covered by PV panels). All above lends themselves to the additional cost. However, it is worthy to be noted: not all of those contribute to the sustainability of the buildings.

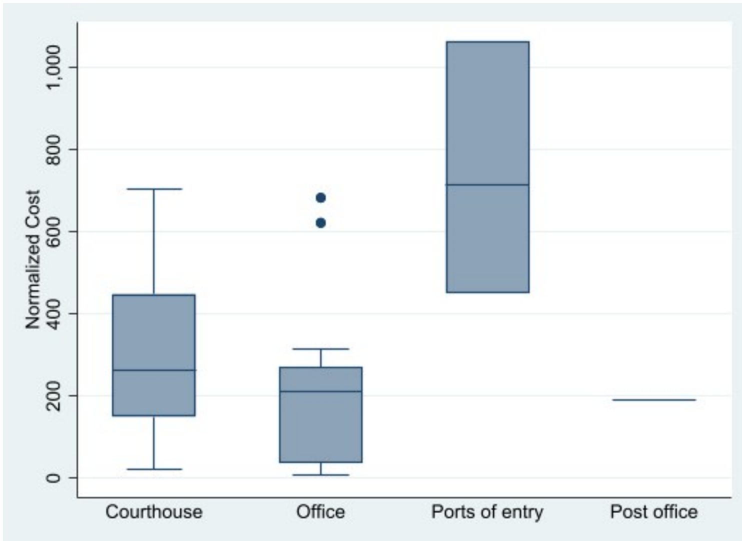


Figure 5.7 Cost variance per building types

Figure 5.8 San Ysidro Land Port roof covered by PV panels

5.2.5 Summary

When comparing the GSA LEED buildings to conventional (non-LEED) buildings, the average new GSA LEED building's construction cost is lower than the average cost of conventional (mid-rise, non-LEED) office buildings, \$425/ft^2 v.s \$562/ ft^2 (Gerardi, 2021).

The average GSA LEED renovation projects' construction of cost is lower than that of conventional buildings, \$204/ ft^2 v.s \$450/ ft^2.

Besides the difference in spatial and program requirement, and the financial resources, one obvious difference between GSA buildings and non-GSA buildings is the project team. GSA project like other federal contracted projects, has requirement for design team and construction team for security reason, and it is a lengthy process for firms and teams to get certification and clearance to work on GSA projects. Consequently, the certified GSA contractors often get repetitive opportunities to work on GSA projects, that helps design teams and contractors to build up the experience and skills, and team can develop better collaboration after they work on several projects together. More experienced and skilled team working repetitively together can contribute to the control of cost overrun and budget overrun, consequently, reduce the final total construction cost. Such hypothesis was then tested using SEM and explained in Chapter 6.

5.3 Project Team Characteristics Data Collection

As explained in Chapter 4.2.2, six indicators measuring project team characteristics influence are derived from the meta-analysis: *collaboration* (Iyer & Jha, 2005) , *communication* (Meng et al., 2011), *skill*, *experience* and *innovation* (Ozorhon & Oral, 2017), and *project procurement.* Table 5.1 demonstrates the data source and type, the detailed explanation for each dimension is followed.

Table 5.1 Data category, resource, and value

Data	Resource	Description	Data Type
Procurement	Online Project website, statement, records	1 = best value, 2 = low bid, 3 = sole source selection, 4 = qualifications-based	Quality
Skill	Online ENR ranking	1 = no skill, 2 = little skill, 3 = moderate skill, 4 = specialist, 5 = leading experts	Quality
Experience	Online ENR ranking	1 = rank >80, 2 = rank (41–80), 3 = rank (21–40), 4 = rank (6-20), 5 = rank top 5	Quality
Collaboration	Online Project website, statement, records	1 = redundant (>50), 2 = inefficient (41-50), 3 = neutral (31-40), 4 = efficient (21-30), 5 = lean (1-20)	Quality
Communication	Online Project website, statement, records	1 = bad, 5 = good	Quantity
Innovation	LEED Score	1 = bad, 6 = good (LEED points)	Quantity

5.3.1 Procurement

Procurement method selected for project is often affected by multiple factors and more complex than project delivery method. For example, different contract methods such as lump sum and guaranteed maximum price (GMP) may require different procurement methods, different delivery method design-bid-build (DBB) and design-build (DB) may demand different procurement methods as well. In this dissertation study, a classification of various procurement methods specified by Beard et al., (2001) was adopted: *qualifications-based selection*, *best value selection*, *low-bid selection*, *sole source selection*.

Sole source selection involves the direct selection of the project team based on selection factors such as previous experience, technical qualifications and relation with project owners (Beard et al., 2001). Qualifications-based selection is typically done through a request for qualification and using a set of qualitative criteria such as past performance, reputation, technical competence and financial stability. Best value selection use both qualitative and quantitative criteria. In a best value approach, the prospective project team respond to the owner by submitting proposal that are primarily evaluated based on the technical aspects together with the associated cost of the project (Beard et al., 2001). Typically, prequalification of the project team based on technical criteria before the final selection phase can be part of the best value procurement method (El Wardani et al., 2006). Low-bid selection is primarily based on the project cost, that means more than 90% of selection criteria representing the cost concern during the project team procurement selection process. Such selection criteria is often used in the project with a high level of design completion at the time of procurement (Molenaar & Gransberg, 2001).

Government agencies are responsible for collecting and reporting data on federal procurements through Federal Procurement Data System, the information regarding the procurement type of studied projects are found and extracted from the data system and other related project report that can be found online. And the how each type is coded is listed in Table 5.1.

5.3.2 Skill

In this study, skill refers to the project design team's (exclude client) collective skill, which is measured based on the company's (firm's) ranking in the two most recognized ranking systems in the building and construction sector. The first ranking is the Top 100 Green Buildings Design Firms from the ENR website from 2008 to 2020. Companies are ranked "according to revenue for construction or design services generation in the previous year from projects that have been registered with or Certified by a thirdparty organization that sets the standard for measuring a building's or facility's environmental impact, energy efficiency or carbon footprint. Such groups include the U.S. Green Building Council (USGBC) and Green Building Initiative." The second ranking is "Architect 50: Top 50 firms in sustainability", published by "Architect", that is official journal of The American Institute of Architects (AIA), 2012 to 2019 [2]. The sustainability score are derived from five categories: (i) 2030 commitment, (ii) energy and water conservation target achieved by projects, (iii) number of LEED certified employee, (v) number of certified green buildings (LEED, Living Building Challenge, Green Globe, Net Zero, Green Guide for Health Care, Energy Star, Passive House, and other leading certifications).; (vi) the green project that best demonstrated a firm's commitment to sustainability. Four categories are weighted differently, 18%, 18%, 6%, 20% and 38%.

These two rankings have some overlap. For example, HOK as a large design firm is ranked fourth on the 2020 ENR 2020 top 100 Green Building Design Firms list and ten on the 2019 Architect Top 50 Firms in Sustainability list. ZGF ARCHITECTS LLP list as 21 on Architect list, 14 on ENR list. In this case, the researcher used the average of the two rankings as an overall ranking to measure the design team's skill.

5.3.3 Experience

The design team's experience is measured by the overall construction/project experience of sustainable buildings of the team/firm. The measure of the experience level is also based on the ENR ranking. The first ranking is the ENR Top Green Contractors 2007 to 2020. The ranking is based on construction revenue in the previous year in ($)

[2] https://www.architectmagazine.com/architect-50/2012/

millions. Lists from different years are combined, and the final ranking is based on an average ranking of those years. The second ranking is Top 500 Design Firms from 2003 to 2020, and this list includes different firm types. "A" stands for architect, "E" for engineer, "EC" for engineer-contractor, "AE" for architect-engineer, "EA" for engineer-architect, "ENV" for environmental, "GE" for geotechnical engineer, "L" for landscape architect, and "O" for others. These two rankings have some overlap. For example, AECOM as a large design and construction firm is ranked fourth on the 2020 Green Contractor list and second on the 2020 Green Buildings Design Firms list. In this case, the researcher used the average of the two rankings as an overall ranking to measure the design team's skill.

The final ranking of the firm is the average of those years. The final ranking is the average of the two ranking scores; for example, if one project has AECOM as an EA firm (ranked second) and HENSEL PHELPS as a contractor (ranked twelfth), then the final experience score for this project team is equal to seven.

5.3.4 Collaboration

Collaboration is often referred to as "working together" and can be reflected in different forms (Hughes et al., 2012) and relate to the procurement type. The definition adopted in this study was derived from a comprehensive review conducted in 2012, which is closely related to partnering (Hughes et al., 2012). Good coordination and communication between architects, engineers, and quantity surveyors is typically viewed as critical to control the construction cost (Elinwa & Buba, 1993).

5.3.5 Communication

The success of a project is impacted by how efficiently team members can communicate with each other. Meanwhile too much communication can sap team's productivity and ultimately lead to burnout. Communication overload can occur if there is not a proper communication protocol established within the project team (Segerstedt & Olofsson, 2010). In this research, communication is measured by the communication channels using the formula presented in the *Project Management Body of Knowledge*. Communication channels show the way information is shared and flows within the team. It is dependent on the number of key independent players in the project team and reflects the procurement type to a certain extent. For example, in a DBB project, each consultant that is hired and reports to the client is considered as an independent player. However, in DB projects, all consultants are under the design team, which can be combined as one firm, one player. The number of channels is calculated using Equation 4.

$$\text{Communication channels} = N * (N-1) /2 \qquad \text{Equation 4}$$

Where N is the number of primary consultant firms hired; such information is extracted from the project website and project statement.

5.3.6 Innovation

Innovation can be measured by key performance indicators (Banu, 2018), total R&D budget within the organization, R&D output, or number of patents issued from the firm. Although those measures have been extensively used, but they are not sufficient to measure the innovation in construction industry, since construction industry is project-based and the organizational context of construction innovations differs significantly from a great portion of manufacturing innovations (Ozorhon & Oral, 2017).

Since this dissertation research focus on project-specific factors on innovation in sustainable projects, therefore, innovation is measured by the credits received under LEED Innovation category. Total there is 6 credits available regardless the different rating system. The intent of the Innovation credit category is to encourage the projects to achieve exception or innovation performance based on USGBC website information, it covers innovation in design-intent, innovation in design-requirement, and innovation in design-implementation. Innovation in design-intent is to award design teams and projects for exceptional performance above requirements set by LEED, or innovative performance in sustainable building categories not address by the LEED rating system. Innovation in design-requirement ask design team to identity the intent of the proposed innovation credit (in writing) and demonstrate code compliance. There are variety innovations being submitted, such as innovative sustainable waste management, design for flexibility, and others. [3]

5.4 Project Characteristic Data Descriptive Statistic

5.4.1 Building types

GSA owns and lease over 300 million square feet of space in 9,600 buildings in more than 2,200 communities nationwide (*GSA Properties*, n.d.). The GSA buildings

[3] https://www.usgbc.org/innovationcatalog?Version=%22v4%22&Rating+System=%22New+Construction%22

include six building types: office, land port of entry, courthouse, laboratory, data processing center and post offices. As demonstrated in Figure 5.9**Error! Reference source not found.**, the projects included in this study are: offices (58%), courthouses (33%), ports of entry (8%), and post offices (1%). Even though the studied projects do not represent the full range of GSA owned buildings, but the analysis results from this dissertation research can be used to understand the condition and status of GSA owned LEED projects.

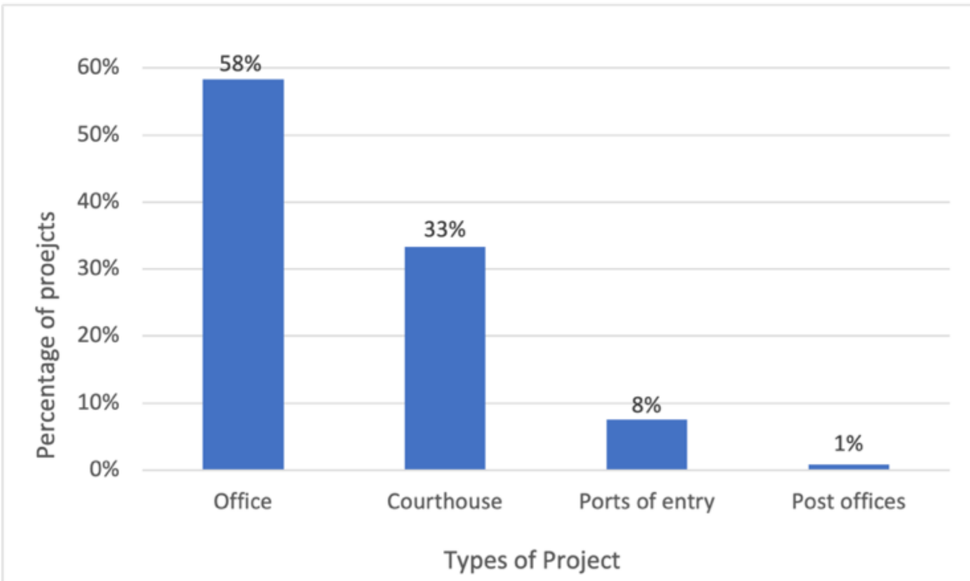


Figure 5.9 Building types included in the study

5.4.2 Building age

As for the age of building (year of original construction) and number of stories of the buildings. Figure 5.10 illustrates the largest portion of buildings, 35% of buildings were built between 2001-2020. 26% buildings were constructed between 1961-1980. 21% buildings were built between 1921-1940, 7% of buildings were built between 1941-1960, 6% of buildings were built before 1920, only 4% buildings was built between 1981 to 2000.

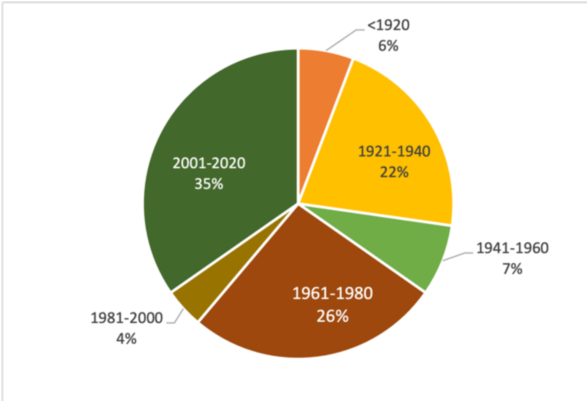


Figure 5.10 Construction year

5.4.3 Project location distribution

The projects included in the study varies in age, location, height (floors) and size. Figure 5.11 shows the geographic distribution of the projects included in this study. District of Columbian has the most projects (n=16), followed by California (n=11), Colorado (n=9) and Washington (n=6). There are eight states only has one case projects included in this study: Georgia, Minnesota, Montana, New Hampshire, Iowa, Louisiana, Wisconsin, and Wyoming. In general, the projects included in this study represent the project population of GSA building in terms of geographic locations.

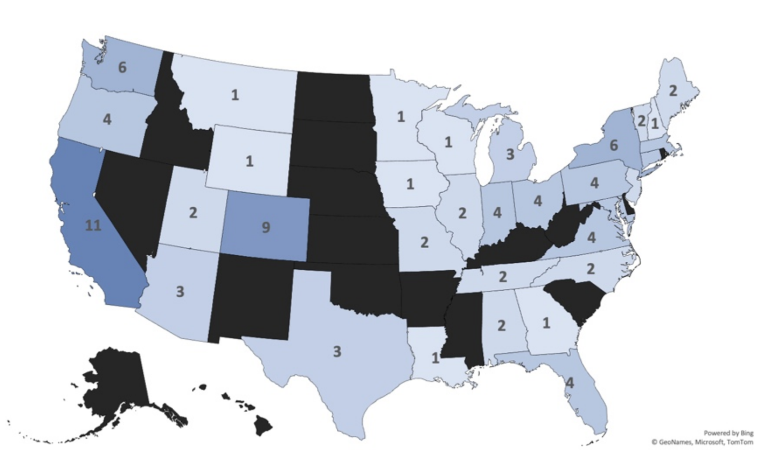


Figure 5.11 Project distribution map

As for the floor area included in this research. As illustrated in Figure 5.12 , Washington DC has the largest floor area, followed by State of California and New York State, that is mainly due to the large number of Federal office buildings located in District of Columbia.

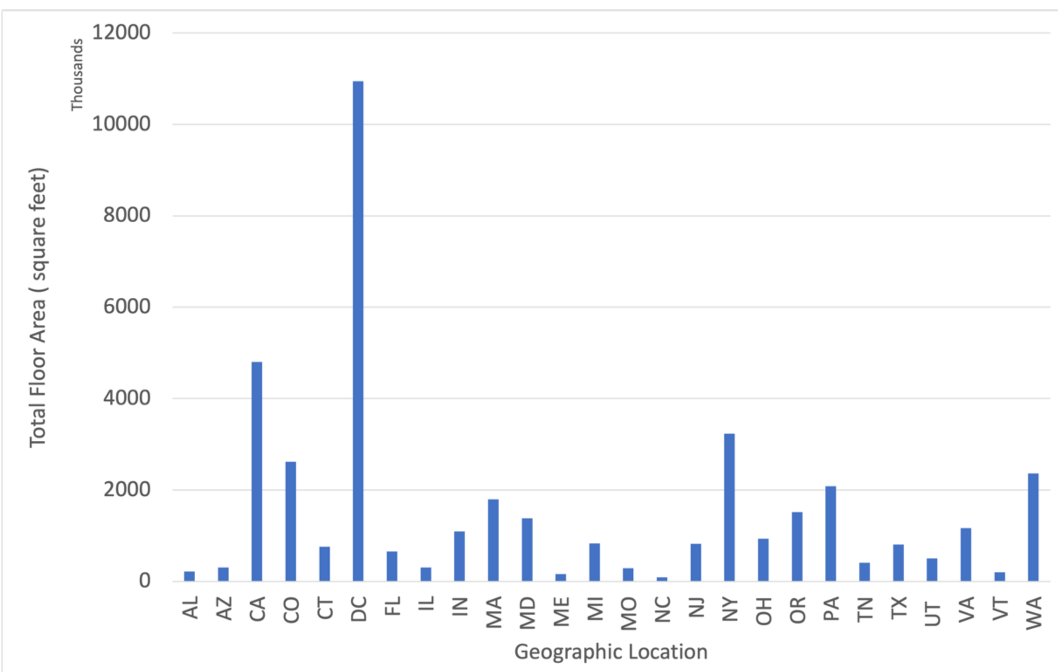


Figure 5.12 Studied project floor area per location

5.4.4 Project level of sustainability achieved

Figure 5.13a illustrates the certification breakdown of studied project, 41% of project are at Certified level, 25% are at Silver level, 28% are at Gold level and the rest 6% are at Platinum level. Figure 5.8b shows even though DC has most LEED buildings but most DC buildings are Certified levels, while California has most Platinum buildings (n=5) leading the level of sustainability.

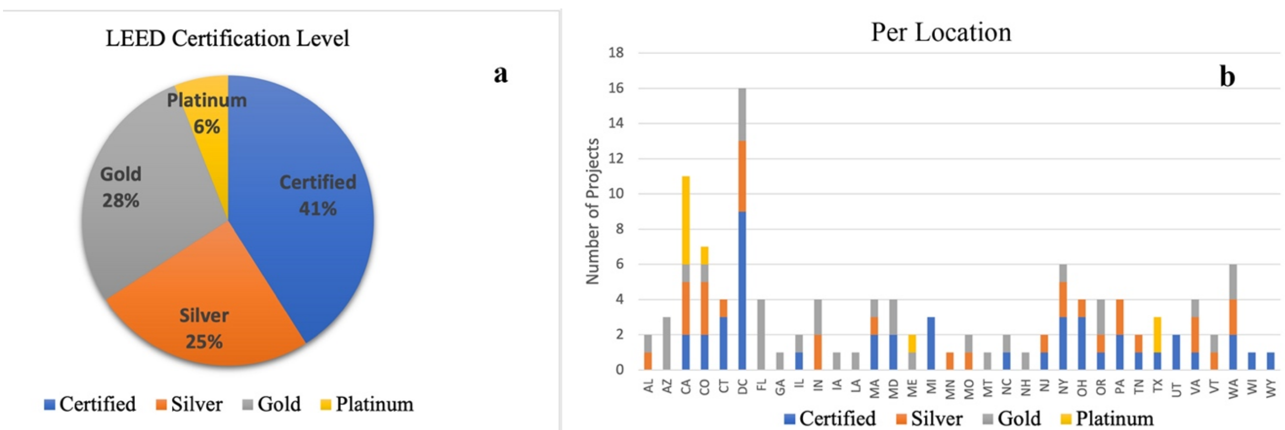


Figure 5.13 Studied projects LEED certification levels

5.4.5 Construction type (scope of work)

As for the type of construction of studied projects illustrated in Figure 5.14, majority project (53%) have limited renovation scope, 26% projects are full renovations, and 20% are new construction. Here the fully renovated project is defined as the project has at least four primary building system fully renovated, retrofit, or upgraded. The primary building systems are: mechanical system (heating, cooling, ventilation), plumbing system, electrical system, building envelope system, fire safety system, vertical transportation system (elevators, etc). In late case studies, projects with limited scope of work are excluded to gain a comprehensive and more accurate understanding the factors of construction cost.

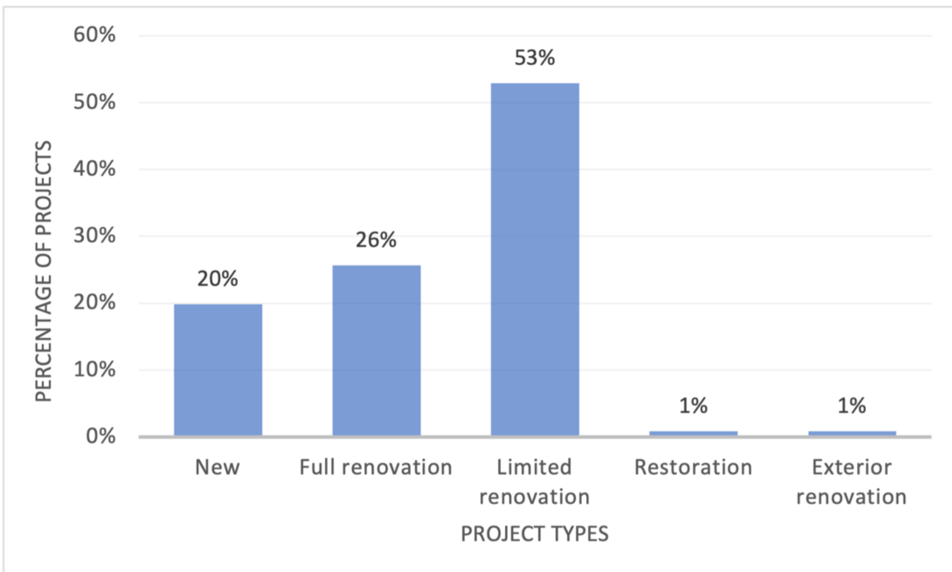


Figure 5.14 Construction types of studied projects

Overall, the projects included in this dissertation study well presents the GSA owned facilities across different geographic locations at different LEED certification levels. The construction cost data are provided by the project owner, that is one of most reliable data sources. As for the data on project team characteristics, since there are quite robust documents and GSA commissioned study on lessons learned on LEED certified projects, therefore, data were able to be extracted, even to the level of direct quote from team members.

5.5 Chapter Summary

Chapter 5 first explain the data collection process and data sources. Then, the descriptive analysis of data, and examination of the data qualitative has been provided. Overall, this chapter sets up the database for the statistical analysis that will be explained in next chapters, Chapter 6 and Chapter 7. One important summary can be made from descriptive statistics of SBCC is that the sustainable building construction cost is comparable to conventional building, if not lower.

Chapter 6 Relation between Construction Cost, Sustainability, Project Team Characteristics and Project Characteristics

This chapter presents the data analysis findings from Phase Three, Quantitative and Qualitative Analysis and Hypothesis Testing. This chapter first provides descriptive statistics of data used for analysis, then the impact of soft cost versus hard cost are determined by regression model. The project factors and project team factors extracted from the meta-analysis are used to as constructs of Structural Equation model (SEM), model specification, analysis steps are explained. At the end the SEM analysis results and the hypothesis testing results are summarized and explained. Table 6.1 listed the hypothesis tested.

Table 6.1 Tested Hypothesis

Hypothesis	Description
H1a	There is no correlation between the construction cost and the level of sustainability
H1b	The primary components contributing to the higher cost of sustainable buildings are derived from the hard costs.
H2a	The project team characteristics has negative effect on the final sustainable building construction cost.
H2b	The projects characteristic has significant effect on the final building construction cost.
H2c	The procurement method has positive relation to project team characteristics.
H2d	The skill level of project team in design has positive relation to project team characteristics.
H2e	The experience level of the project team in design has positive relation to project team characteristics.
H2f	The communication within the project team in design has positive relation to project team characteristics.
H2g	The collaboration within the project team in design has positive relation to project team characteristics.
H2h	The motivation to innovate of the project team in design has positive relation to project team characteristics.

As illustrated in Figure 6.1 the two research objectives addressed are objective 2 and 3.

Objective 2: investigate the soft cost's impact on total construction cost

Objective 3: evaluate the pattern of correlation/covariance among project characters, project team characteristics, and level of sustainability to SBCC

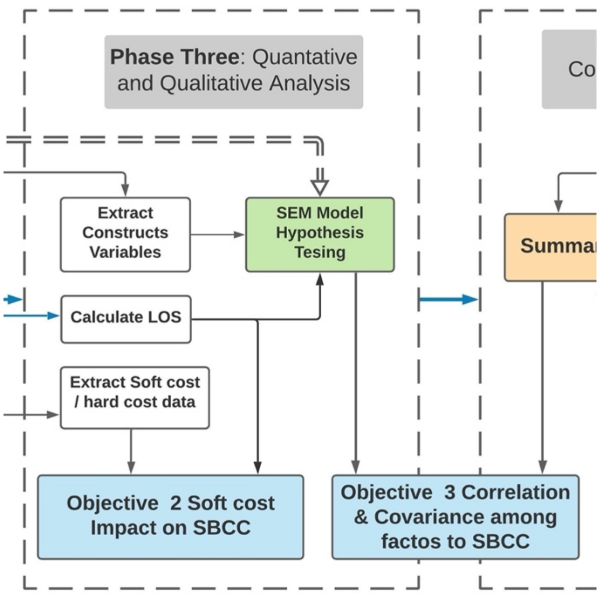


Figure 6.1 Research Phase Three diagram

6.1 SBCC Regression Model Analysis

6.1.1 Relation between level of sustainability and construction cost

Two regression models were created to study the correlation between normalized total construction cost and level of sustainability (LOS). Hypothesis 1a (H1a) was tested (there is no correlation between the construction cost and the level of sustainability). Here, the researcher used two ways to measure the LOS, and first measure is LEED certification level, the second is the overall LEED score the projects received.

The first measure is to assign the four LEED certification levels (Certified, Silver, Gold, and Platinum) with the number 1 through 4, 1 represent Certified, 4 represent Platinum. For the second measure, the researcher normalized LEED score. To achieve each certification level, certain points are required, but the numbers of points required for the same level varies depend on which LEED rating system, and which version are applied to the projects. For example, current LEED v4.1for Building Design and Construction (LEED BD+C) has maximum 110 points, and to achieve Certified level, at least 40 points are required. Silver certification level requires 50-59 points, Gold certification requires 60-79 points and Platinum requires 80 or more points. However, the third version of LEED BD+C released in late 2005, only have total 69 available points, 26-32 is required for Certified, 33-38 points are required for Silver, 39-51 points are required for Gold, lastly Platinum certification needs 52-69 points. Meanwhile, LEED v4.1 O+M, Existing Buildings Operations and Maintenance has total 100 points, but the certification levels are the same to LEED BD+C. The projects included in this study are certified under different rating system, and/or under different version. The summary of the different system and points are listed in Table 6.2.

Table 6.2 Rating systems certification levels and points

LEED SYSTEM	Available points	Certified	Silver	Gold	Platinum
BD+C (v2009)	110	40-49	50-59	60-79	80+
O+M	100	40-49	50-59	60-79	80+
ID+C	110	40-49	50-59	60-79	80+
BD+C (v2.1)	69	26-32	33-38	39-51	52-69

Because of the differences among different LEED versions, to have a fair comparison, the LEED score is normalized by the percentage of the points received for certification. For example, in a LEED BD+C (v2009) system, the maximum points is 110, a Silver project got 54 credits out of the 110 maximum credits available. Then its points score is calculated as 54/110, equally to 0.49. In a LEED O+M system, (for existing building) there is total 100 points, a Silver project got 54 credits out of the 100 maximum credits available. Then its points score is calculated as 54/100, equally to 0.59.

As included in Table 6.3, when measured by the normalized LEED score, there is no statically significant correlation ($p>0.05$) between normalized total construction cost and level of sustainability. When measured by the LEED certification level, the data shows statically significant correlation ($p<0.05$) between normalized total construction cost and level of certification (Certified, Silver, Gold, and Platinum). However, only 19.4% of the variance of LOS can be explained by the cost difference.

Table 6.3 Regression analysis between LOS and Construction Cost

Measure (LOS)	**R Square**	**P-value**	**Coefficients**
LEED Normalized Score	0.066	0.00576	515.85
LEED Certification Level	0.194	1.0512E-06	106.71

Based on the results from the two regression models, the researcher concluded the result for H1a (relation between the normalized construction cost and LOS) is inconclusive. And even the conclusion was that there is correlation between those two, the coefficient is very low, that is an indication there are other parameters that have critical influence on construction cost, other than the level of sustainability achieved.

6.1.2 Construction cost per LOS

Because the result of H1a is inconclusive, to understand how the construction costs are reflected in different sustainability levels, the researcher then examined the projects based on their LOS (measure by LEED points). As illustrated in Figure 6.2, blue round dot represents LEED Certified, orange diamond represents LEED Silver, grey triangle represents LEED Gold, and yellow square represents LEED Platinum. Y axis is the percentage of the LEED points the project obtained, the more points, the higher the reward, the higher the certification level and LOS.

Figure 6.2 shows the average cost of all LEED buildings is \$288/ft^2, the average cost of Certified is \$93/ft^2, the average cost of Silver is \$161/ft^2, the average cost of Gold is \$373/ft^2, and the average cost of Platinum is \$322/ft^2. In general, there is **NO** clear indication that higher construction cost is associated with the higher rating level and score. The sample data suggests the LEED Gold level projects has higher average cost than that of LEED Platinum buildings, which is indication that there are other factors moderate the cost of higher LEED level projects.

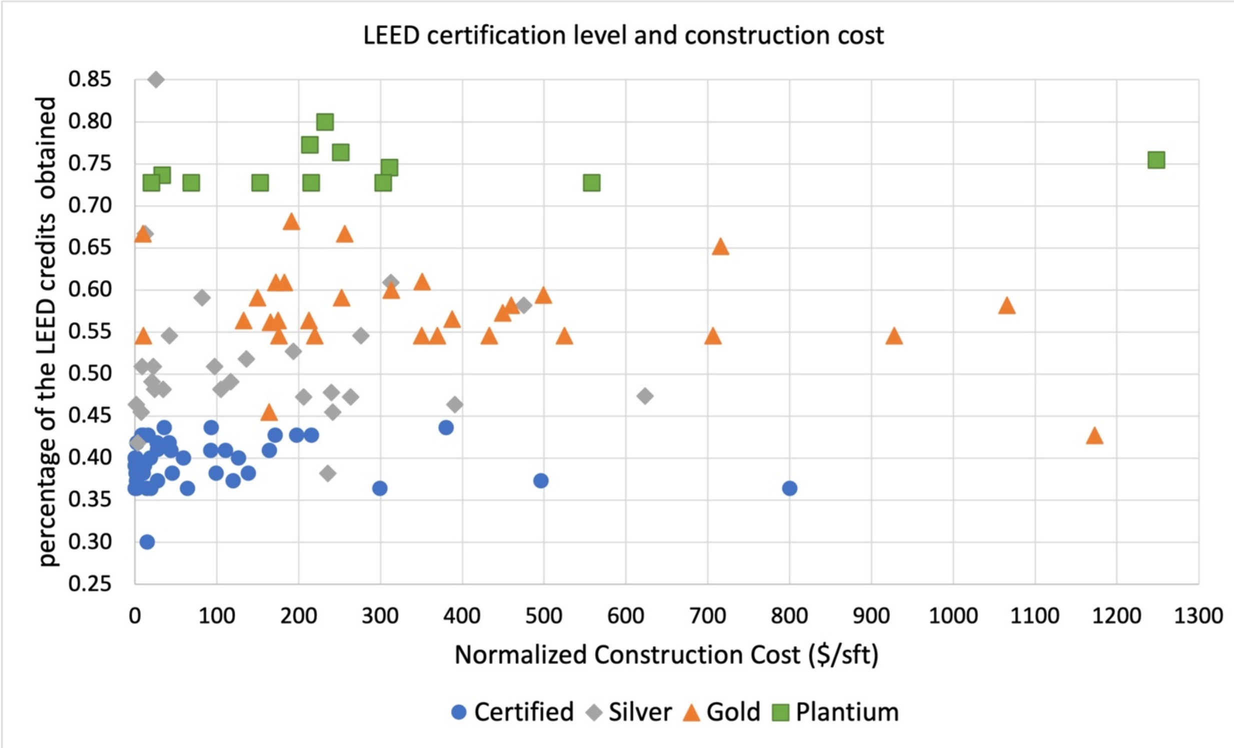


Figure 6.2 Construction cost and LEED certification level

Then, the researcher investigated the difference of construction cost per certification level, and their comparison to others. Figure 6.3 demonstrates three findings were observed: (1) there are similarities among the low-cost projects, (2) there are similarities among the Silver level projects, (3) the high construction cost of Certified level building may be related to the higher security and safety requirements, rather than the sustainability pursue.

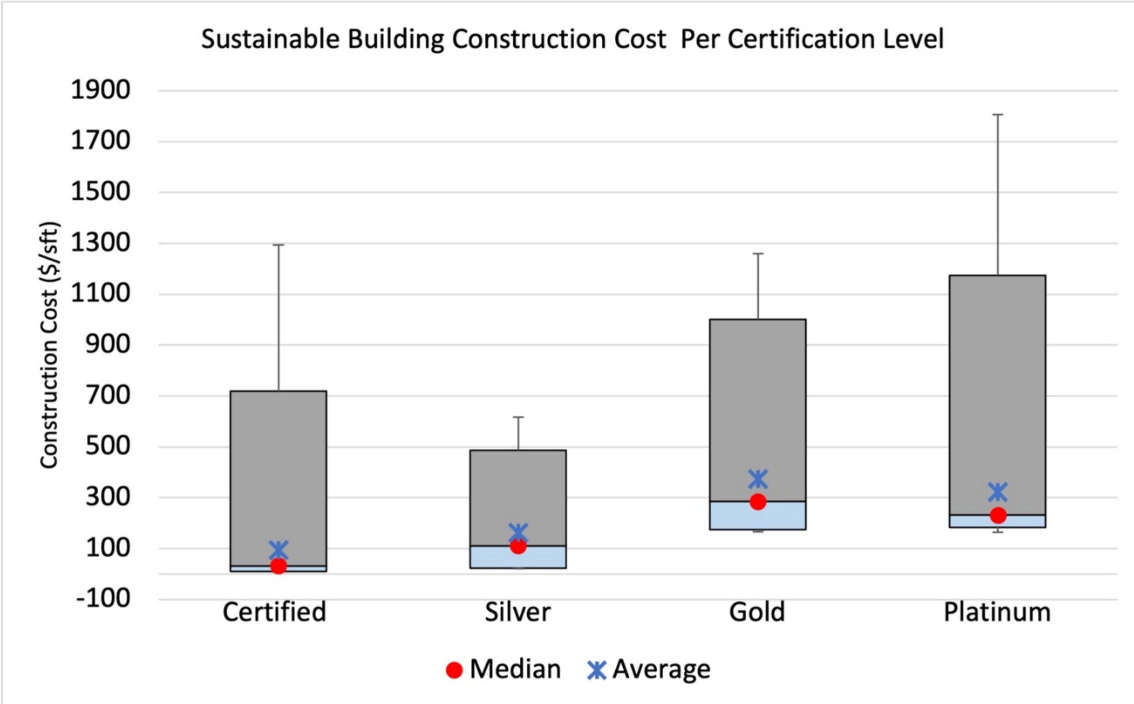


Figure 6.3 Construction cost per certification level

First, across all LEED Certification levels, the grey box (Q3 tile) indicates the large cost variation among the projects that the construction costs are above average. On the other hand, the cost variants among projects that have lower construction cost than the average is small. Meanwhile, as showed in Table 6.4, the projects with lower-than-average construction cost are the majority (Certified = 68%, Silver = 57%, Gold = 63%, Platinum = 82%). Such combination suggests that there are some common practices or similarity among low-cost projects, that leads to the similar normalized construction cost regardless the size the location of the projects.

Table 6.4 Percentage of project regarding construction cost

	Certified	**Silver**	**Gold**	**Platinum**

Percentage of projects above average construction cost				
	32%	43%	37%	18%
Percentage of projects below average construction cost				
	68%	57%	63%	82%

Second, the box plot of projects cost at Silver level is comparatively shorter than those of other certified levels. Shorter box plot is the indication that the projects certified at Silver level have similar normalized construction cost, that suggest there are some common practices, or similarity among those projects. Such common practice and similarity contribute to the closely distributed normalized construction cost.

Third, the upper whisker for certified and Platinum projects are much longer than that of Silver and Gold, that suggest within the top 25% cost projects of certified and Platinum projects, there is large cost variance, and most likely such variance is caused by few outliners with very high construction cost. For instance, the highest cost of LEED Platinum project is $1605/ft^2$, which is an office building at port of entry. Compared to regular GSA office building, in addition to have blast resistance design, port of entry has higher requirement for security and some unique plan layout requirement. Consequently, the researcher speculate that the high cost is largely induced by the higher security and safety requirement, instead of sustainability consideration.

6.1.3 Influential factors: soft cost vs hard cost

Hypothesis 1b (H1b) was tested (the primary components contributing to the higher cost of sustainable buildings are derived from the hard costs). As illustrated in Table 6.5, the regression model shows hard cost and design cost were both statistically significant ($p<0.05$), and they were independent to each other. Within the soft cost, design cost was significant (p<0.05), while the influence of the cost of management and inspection was not statistically significant to the construction cost (p>0.05). 95.6% of construction cost variance can be explained by the change in hard cost and design cost, they have similar level of influence. Such finding is critical, that demonstrate even though the design cost is very small portion of the total construction cost, range from 2% to 19% in the studied projects, but it has the same level of impact on total construction cost as that from hard cost. The explanation of such findings is in align with the effort curve described in Chapter 1, that states the most important decisions that have determining influence on the construction cost are often made by the design team in the early stage, and reflected on design cost.

Table 6.5 Regression analysis results: hard cost vas soft cost

Variables		R square	ANOVA F Significance	ANOVA F	P-value	Coefficients
Hard Cost		0.956	< 0.05	94.97	< 0.05	0.993
Soft Cost	Design				< 0.05	0.906
	Management				0.122	0.420

From results of the SBCC data statistical analysis, conclusion can be made to understand the impact and importance of **design cost** to the total construction cost. Even though there is wide range of variation in the normalized construction cost per building types, construction types and geographic locations across all different level of LEED certifications and measured LOS, the researcher found the significant impact of soft cost, specifically **design cost** on the total construction cost. To further understand the drivers and factors related design cost, project team characteristics and project factors that exacted from SBCC database are used to construct SEM. In the following sections, SEM model specification and analysis results are explained.

6.2 SEM Research Design

The objective of this SEM analysis is to identify the causal relationship between the SBCC and the project characteristics and project team characteristics by executing a quantitative data analysis on built GSA LEED projects. The project characteristics are the indication of hard cost, and project team characteristics are the indicators of soft cost. The project team characteristics is a latent variable used to measure the project team's characteristics, especially during the early design stage.

Normally, SEM analysis work with a large sample size, due to its goal of testing hypothesis and model fitting. A major differences exists in the definition of the "large" across different disciplines (Alaloul et al., 2020). The rule of thumb for the acceptable sample size is between 20:1 to 5:1. The desirable size is 20:1, that is the ratio for the number of subjects to the number of model variables. However, a 10:1 is more realistic target. If the ratio is less than 5:1, the estimation maybe unstable. There are two different school of thoughts regarding determination of data sample size. (Creswell & Creswell, 2017) stated it is essential to define the lowest sample size required to achieve the desired degree of statistical power with a suggested model. However, Kline (2015) proposed a "critical sample size' concept, with an emphasis on quality of most relevant data sample, rather than the quantity of the data. As for maximum likelihood analysis, the sample size can be as small as 50. In addition, the optimized sample is also dependent on the model complexity, levels, and data distribution properties. Distribution normality is crucial to assess the correlation and generate summary. The sampling distribution is considered to be normally distributed based on the following condition: (a) sample size (n) is larger than 30, (b) no extreme values (Lumen, 2021).

As show in Figure 6.4, a normal SEM model building and analysis consists of five steps. The first step was to design the research and model specifications. The second stage was to collect data based on the specified research concept. The third step was to develop a hypothetical SEM model for testing. The validity of the proposed hypothetical model was then tested using various goodness of fit (GOF) indices. The fourth step was to test the hypothesis using collected data from the previous steps and the evaluation results. The last step was to report the results and findings. A detailed explanation for each of the steps is explained in the following sections. Since the SBCC database has already been created, therefore the second step was not necessary for this SEM analysis. The detailed explanation for the rest steps are followed.

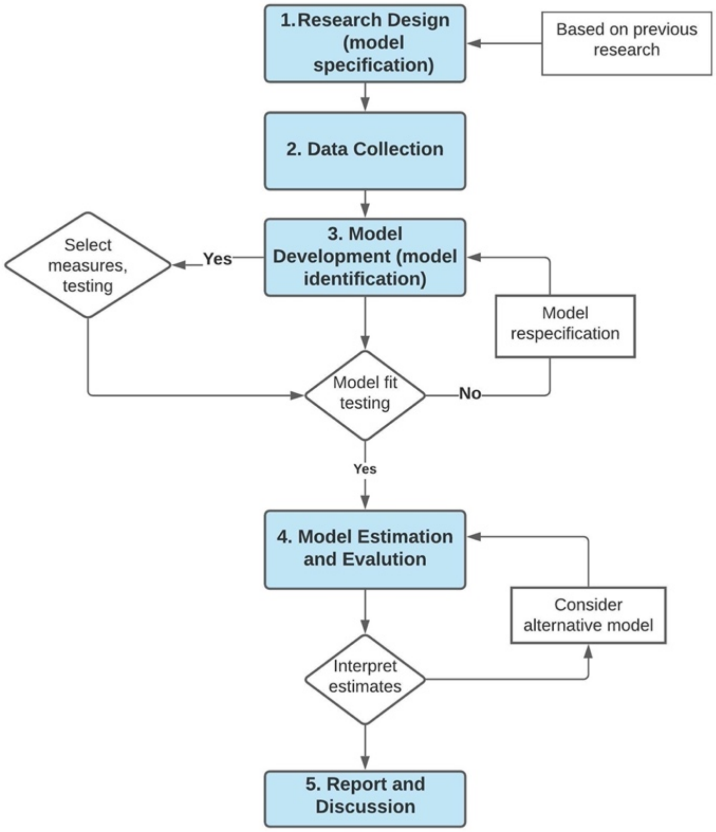


Figure 6.4 Research framework and flow for SEM analysis

6.2.1 Model specification

The first step is to specify the model. The various characteristics that affect the sustainable building construction cost, based on meta-analysis of previous research (refer to Chapter 4), can generally be categorized into two groups: the project team characteristics that reflect various project team characteristics, and the project characteristics that reflect the project physical conditions. Initially, six variables (B1-B6) extracted to measure the project team characteristics, seven variables extracted to measure project characteristics (B7-B13, including level of sustainability). Several steps are involved for developing, identifying, and testing the model. The purpose of the test is to confirm the ability of the proposed SEM conceptual model fit with the collected data. The following steps and testing were taken to identify the optimized model fit with the collected data.

6.2.2 Model development: measure variables

As illustrated in Figure 6.5, six project team characteristics are: (B1) procurement, (B2) skill, (B3) experience, (B4) communication, (B5) collaboration, and (B6) motivation to innovate. Seven project characteristics factors are: (B7) level of sustainability, (B8) building type, (B9) construction type, (B10) technical complexity, (B11) project location, (B12) project scale, and (B13) material availability (as a proxy for supply chain maturity).

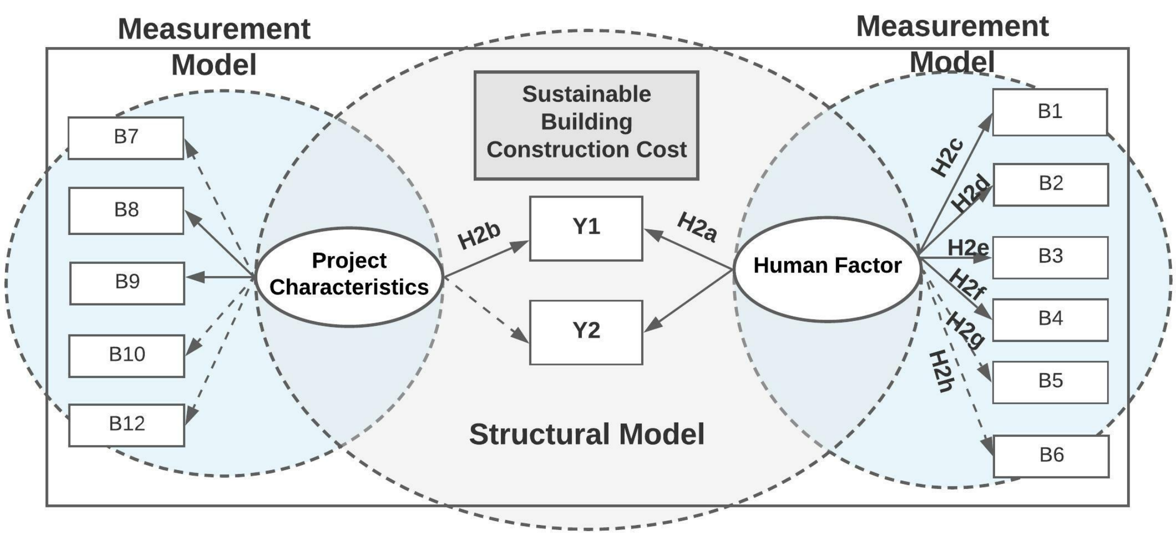


Figure 6.5 Specified SEM and tested hypothesis (H2a - H2h)

Table 6.6 shows all variables were evaluated based on nominal and ordinal scales, from one to five, in the third columns. For example, for the <u>project scale</u> (B12), if the project cost \$1 million to \$3 million, then it was given a score of 1 on the ordinal scale;

while for the team's skill (B2), it was given a rating based on the ordinal scale, consisting of one (no skill) to five (leading experts) points.

Skill (B2) refers to the project design team's (exclude client) collective skill, which is measured based on the company's (firm's) ranking in the two most recognized ranking systems in the building and construction sector. The first ranking system is the Top 100 Green Buildings Design Firms from Engineering News-Record (ENR) website from 2008 to 2020. The second ranking is Top 50 firms in sustainability from "Architect" ranking. "Architect" magazine is the only official publication form The American Institute of Architects, that ranking from AIA represents the most comprehensive evaluation from architecture field. If the average ranking of firm is within top 5, then this firm can be considered as leading expert. A firm with the average ranking between 6-20 is considered as specialist, a firm with the ranking between 21 and 30 is considered with moderate skill, a firm with the ranking between 31 and 50 is considered with certain skill, a firm are not included in the ranking is considered with no skill.

Experience (B3) is measured by the overall construction/project experience of the team. The measure of the experience level is also based on two ENR rankings. Top 500 Design Firms from 2003 to 2020, and Top 100 Green Contractors. The final score for experience is the average of these two rankings. If the average ranking within top 5, then the design team experience score is 5; score 4 represent the average ranking between 6 and 20; score 3 represent average ranking between 21 and 40; score 2 represent average ranking between 41 and 80, score 1 represent average ranking below 80.

Communication (B5) is measured by the communication channels using the formula presented in the *Project Management Body of Knowledge*. (Refer to Chapter 5.2.5). The project has communication channels over 50 is considered as redundant, its score is 1.A project has official channel less than 20 is considered lean, so its communication score is 5. For example, Wayne N. Aspinall Federal Building and U.S Courthouse is a Design-Build project. The Design-Build include contractor, lead design architect, engineering, interior design and historical preservation. Beside the Design-Build team, GSA (owner) also hired three separate consultants for fire protection, blast protection and civil engineering. Jacob was hired as construction management assistant, and M.E group was hired as commissioning agent. Total, there are six primary consultant firms hired for this project. So the total communication channels is calculated as N * (N-1) /2 = 6 * (6-1)/ 2 = 15, that is scored as 5 (lean).

The assessment of collaboration (B5) is derived from the case report, project statements and description, whether the team members felt they had good collaboration and partnership during the project design phase. For instance, some project team has co-located office during the project, which largely reflect the team's commitment to collaboration, and meanwhile being physically located in the same office space also facilitate better communication and collaboration.

Innovation (B6) is measured by the points the project received under LEED Innovation category. There is total 6 points available, therefore innovation is the only variable is measured from 1 to 6.

Table 6.6 Variables affecting the sustainable building construction cost

No.	Variables	Description
Project Team characteristic		
B1	Procurement	1 = best value, 2 = low bid, 3 = sole source selection, 4 = qualifications-based
B2	Skill	1 = no skill, 2 = little skill, 3 = moderate skill, 4 = specialist, 5 = leading experts
B3	Experience	1 = rank >80, 2 = rank (41–80), 3 = rank (21–40), 4 = rank (6-20), 5 = rank top 5
B4	Communication	1 = redundant (>50), 2 = inefficient (41-50), 3 = neutral (31-40), 4 = efficient (21-30), 5 = lean (1-20)
B5	Collaboration	1 = bad, 5 = good
B6	Motivation to innovate	1 = low, 6 = high (LEED points)
Project characteristic		
B7	Level of sustainability	1 = LEED certified, 2 = LEED silver, 3 = LEED gold, 4 = LEED platinum, 5 = zero energy certified
B8	Building type	1= Office, 2 = Courthouse, 3 = Port of entry, 4 = Post office, 5 = Inspection
B9	Construction type	1 = new construction, 2 = full renovation, 3 = limited renovation, 4 = restoration, 5 = others
B10	Technical complexity	1= 0.5< ~ < 0.9, 2= 0.91< ~ < 1.5, 3= 1.51< ~ < 2, 4= 2.1< ~ < 2.84, 5 = > 2.85
B11	Project location	1 = West, 2 = South Atlantic, 3 = Northeast 4 = South, 5 = Midwest
B12	Project scale	1 = 1< ~ < 50,000 ft^2, 2 = 50,001 < ~ < 200,000, 3 = 200,001 < ~ < 500,000, 4 = 500,001< ~ < 1,000,000, 5 = > 1,000,000.
B13	Material availability	1 = 2 point, 2 = 3-4 point, 3 = 5-6 point, 4 = 7-8 point, 5 = > 8points

All case projects were evaluated based on nominal and ordinal scales, from one to five. For example, for the project scale (B12), if the project total gross area is less than 50,000 ft^2, then it was given a score of 1 on the ordinal scale; if 50,001 ft^2 to 200,000 ft^2, 2 points; if 200,001 ft^2 to 500,000 ft^2, 3 points; if 500,001 ft^2 to 1,000,000 ft^2, 4 points; if over 1,000,000 ft^2, 5 points. The measure of B8, B9, B11 is straightforward as described in Table 6.6.

Technical complexity (B10) is measured using the LEED credits score in the Energy and Atmosphere category since this category is considered as hallmark of a high performance building, and a feature expected of LEED buildings by the broader real estate market (Winters et al., 2014). There is total 35 points available, including three required points. For example, Wayne Aspinall Federal Building is LEED Platinum, it received 33 points, so the normalized score is 33/35 = 0.94. In addition, the complexity is also measured by the sophistication of the building envelope system of studied projects. Some projects has conventional façade system, and others have double skin façade or automated façade. The score is given as 1 to 5, 1 being the most conventional, 5 being the most sophistic. Using Wayne Aspinall Federal Building as a example, the average of those two score is 0.94 + 5 = 2.97. It is more than 2.85, therefore the final score is 5 (refer to Table 6.6).

Material availability(B13) is used as a proxy for supply chain maturity, it is measured by the points the project received under LEED Material category. There is total ten points available, including two required points. A project got the minimal required two points was given score of 1; if 3-4 points, score 2; if 5-6 points, score 3; if 7-8 points, score 4; if > 8 points, score 5.

6.2.3 Correlation test

First, the correlation test was performed to test the correlation among the collected data (variables). Bartlett's test of sphericity and Kaiser-Meyer-Olkin (KMO) were used to identify whether the collected variables were related and to provide unique information about the factors the researcher is attempting to identify. Bartlett's test checks whether there are redundancies between variables that can be summarized to some factors. The significance of Bartlett's test ($p<0.05$) is to indicate if there are sufficient intercorrelations among the variables, making it worthy to conduct a factor analysis in the next step (Glen, n.d.-b). KMO is a measurement that indicates the proportion of variance in the variables that may be caused by some underlying factors. 0.50 is the minimal value for indicating that a factor analysis as a next step may be useful, and the larger KMO values are better. The results of the correlation testing and KMO values are listed and explained in the section 6.4 findings.

6.2.4 Exploratory factor analysis

After the correlation test, a factor loading matrix was generated to indicate the relative importance of each variable. A factor and principal component analysis was conducted in software called STATA to uncover the grouping of underlying factors of collected variables. Table 6.7 illustrates the rotated factor matrix; for example, variables B1 through B4 are grouped under factor 1, and B6 and B7 are under factor 2. This correlation and grouping are indicators of common underlying factors for those variables, which used by researcher for further exploration of correlation and covariance among variables using SEM. The data included in Table 6.7 Rotated factor matrix are reorganized in Table 6.9 to present exploratory factor analysis results (refer to Section 6.4.2 for explanation)

Table 6.7 Rotated factor matrix

Variable	**Factor 1**	**Factor 2**	**Factor 3**	**Uniqueness**

B1	Procurement	0.6501	0.1995	-0.072	0.334
B2	Skill	0.9005	0.1746	-0.2032	0.1107
B3	Experience	0.8758	0.0539	-0.2618	0.1442
B4	Communication	0.653	-0.1353	-0.2803	0.4472
B6	Innovation	0.6146	-0.2142	0.0777	0.5011
B5	Collaboration	0.4364	0.2268	-0.0321	0.2311
B7	LOS	0.2547	-0.6123	0.3	0.1393
B12	Project scale	-0.0464	0.5533	0.3097	0.3489
B9	Construction type	0.1163	0.7633	0.1503	0.2837
B13	Material availability	0.2958	-0.3771	0.7407	0.1285
B8	Building type	0.4062	-0.4406	-0.6194	0.2214
B10	Technical complexity	-0.1121	0.2567	0.2319	0.3567
B11	Project location	0.0315	0.3205	-0.3294	0.3023

Second, after uncovering the potential factors, Cronbach's alpha (α) was used to test the internal data consistency (reliability). Cronbach's alpha is often used to test how closely related the set of variables identified under the underlying factors are as a group; therefore, three α were obtained to test the data consistency and reliability under factors 1, 2, and 3, respectively. The test results are included in Table 6.9. An α value of 0.7 or higher is considered "acceptable" (UCLA, 2021). The results are explained in the section 6.4 findings.

6.2.5 Model specification and re-specification

Based on the results from the factor analysis, pearson correlation analysis, and data reliability test, variables and factors without statistical significance were excluded. The process of excluding variables and adjusting variable grouping is called respecification. Respecification allows for an evaluation hypothesis and enhances the understanding of how changes in one factor can affect the overall outcome of the analysis, which is particularly important in the modeling building stage (Sales et al., 2015). As stated by Kline (2015), early SEM generally depends on the hypothesis and previous empirical findings, which have a minimum potential to satisfy the standard indicators of a fit model. An optimized structural model should be created based on the suggested model GOF indicators. Multiple GOF indicators were used in this study and explained in section 6.4.4. Respecified factors and variables often depend on the basic knowledge of the theory and literature on the studied subject. In this study, respecifying the variables relied on the previous theory developed on sustainable building construction cost and the researcher's research and practice experience in the field of sustainable building.

6.2.6 SEM model estimation and evaluation

The last step is model estimation and evaluation. Model estimation is the process to compute the best possible set of estimated parameters to represent the given data. The default and commonly used estimator in SEM is maximum likelihood (ML), and the model assumes multivariate normality and assumes variables are standardized. ML is a full information method, which means that it estimates all variables simultaneously and is therefore unbiased, efficient, and consistent. However, estimating variables at the same time also means that if a model is mis-specificized, errors in one part of the model can affect variables' estimates in a different part of the model—a process known as error propagation (Glen, n.d.-a). SEM was chosen over GSEM in STATA for the following reasons: (1) SEM is more efficient than GSEM, (2) SEM can handle variance-covariance data and provide all types of fit statistics, (3) and SEM can test indirect paths. After the model is estimated, there are three primary criteria used to evaluate the model and estimation results: (a) the fitness of the model, (b) whether there are negative variance problems (Haywood cases), and (c) whether the path and each parameter estimation result can be interpreted. The explanation for each criterion can be found in the following section.

6.3 SEM Analysis Findings and Discussion

6.3.1 Correlation analysis

A Pearson correlation analysis was conducted to determine an estimate of the interrelationships among the variables (refer to Table 6.8). The statistical significance of correlation was determined at $p < 0.05$; it appears as an asterisk (*) next to the correlation value. A positive value denotes a positive linear correlation, and a negative value denotes a negative linear correlation. The closer the value to -1 or +1, the stronger the influence and correlation. The goal in this analysis was to identify the relation between project characteristic factors and project team characteristics. To interpret the degree of correlation, a high degree of correlation is between <u>0.7 and 1</u> (1 is a perfect correlation), a moderate correlation is between <u>0.3 and 0.69,</u> and a low degree (weak) of correlation is between <u>0 and 0.29</u> (Ratner, 2009).

For example, the correlation between B1 and B2 is 0.5831; with an asterisk, it means there is a moderate positive correlation between B1 and B2. Table 6.8 demonstrates significant relationships among several variables, with three observations of importance:

A. Level of sustainability (B7) has a moderately positive relation with team skill (B2), experience (B3), and innovation (B6).

B. Construction type (B9) has a moderately negative relation with the level of sustainability (B7) and building type (B8).

C. Team skill (B2) has a strong positive relation with team experience (B3) and a moderately positive relation with communication (B4), collaboration (B5), and innovation (B6), hence B2 could be used as a primary proxy to measure the project team characteristics and project team characteristics.

Table 6.8 Pearson correlation matrices

			B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
Huamn Factor	Procurement	B1	1												
	Skill	B2	0.5831*	1											
	Experience	B3	0.5330*	0.9141*	1										
	Communication	B4	0.3295*	0.4971*	0.5523*	1									
	Collaboration	B5	0.035	0.4365*	0.3424*	0.2715	1								
	Innovation	B6	0.182	0.4507*	0.4120*	0.3555*	0.247	1							
Project Charact	LOS	B7	0.288	0.3201*	0.3621*	0.2927	-0.083	0.3365*	1						
	Building Types	B8	-0.069	-0.168	-0.108	0.0227	-0.216	-0.1781	0.0637	1					
	ConstructionTypes	B9	0.033	-0.023	-0.107	-0.1185	-0.006	-0.2374	-0.3729*	-0.3810*	1				
	Energy (technical	B10	0.185	0.2029	0.115	0.007	-0.061	0.2445	0.0978	-0.098	0.081	1			
	Location	B11	0.028	0.08	0.062	-0.0305	-0.111	-0.1482	-0.15	0.008	0.258	-0.04			
	Project Scale	B12	0.3783*	0.2377	0.152	0.0162	0.227	-0.0239	-0.063	-0.226	0.218	0.3331*	-0.082	1	
	Material Selection	B13	0.022	0.0084	0.018	0.0494	0.028	0.1155	0.5779*	-0.3142*	-0.128	-0.05	-0.116	0.037	1

6.3.2 Exploratory factor analysis and scale reliability test

After gaining an overall understanding of the correlation among variables, the exploratory factor analysis (EFA) was used to discover the underlying factors (constructs) of the variables measured in this study (refer to Table 6.9). The sample-to-item ratios were higher than 10:1, meeting the recommended minimum requirement of 5:1 (O'Rourke et al., 2013). By using the principal factor analysis with varimax rotation, three factors were identified with Eigenvalues greater than 1 that should be retained. The three factors are the project team characteristics, *project character one*, and *project character two*. The KMO values for the project team characteristics, project scale, and project type are 0.660, 0.552, and 0.612, respectively, which are all greater than the recommended minimum value of 0.5 (Kaiser, 1958). Among the initial 13 variables, the factor loadings of 11 variables were higher than (0.5); variables B11 and B13, which had a loading factor less than (0.5), were removed from further analysis (Field, 2005).

After removing the insignificant variables (B11 and B13), a reliability test was conducted to identify the internal consistency of the variables within each factor using Cronbach's alpha value (refer to the sixth column in Table 6.9), The acceptable threshold of $\boldsymbol{\alpha}$ is 0.7. The project team characteristics and project scale have an α value of 0.8047 and 0.7476, respectively, while the value of the project type is below the threshold. However, when author calculate variables under the project scale and project type together and consider them under the "project characteristics," then the α value is higher than the requirement; therefore, the author kept the project type in the next step, SEM model testing, and grouped project type together with project scale variables.

Table 6.9 Exploratory factor analysis of the variables

Principal Factor	**Nature**	**Code**	**Variables**	**Factor loading**	$\boldsymbol{\alpha}$
Overall KMO = 0.608					
Project Team Characteristics					0.8047
(KMO = 0.660)	+	B1	Procurement	0.650	
	+	B2	Skill	0.900	
	+	B3	Experience	0.876	
	+	B4	Communication	0.653	
	+	B5	Collaboration	0.636	
	+	B6	Innovation	0.561	
Project Characteristics One					0.7476
(KMO = 0.552)	-	B7	LOS	0.612	
	+	B12	Project size	0.553	
	+	B9	Construction types	0.763	

Project Characteristics Two					
(KMO = 0.612)					0.517
	+	B13	Material	0.232	
	+	B8	Building type	0.603	
	+	B10	Technical complexity	0.735	
	+	B11	Location	0.435	
Note: α = Cronbach's alpha value, KMO = Kaiser-Meyer-Olkin					
+' indicates positive variables, '-' indicates negative variables					

6.3.3 SEM model specification

As shown in Figure 6.6, the final SEM was developed using the results from the Pearson correlation and EFA to further investigate the relationship between project team characteristics , project characteristic and the sustainable building construction cost. The final SEM model is consisted of the structural components and measurement component. The structural comments include which are exogenous variables (project team characteristics and project characteristics) and observed variables (Y1, Y2). The measurement component include the endogenous variables (B1-B12) that reflected by the exogenous variables. Together, the group of variables (observed, exogenous, and endogenous variables) explain the causal relationship between various project characteristics and the construction cost; and the relationship between project team characteristics and the construction cost. The project characteristics included in this study are predetermined and do not have a causal relation to project team characteristics. The final model consists of 10 observed variables "B1–B12," excluding "B11" and Y1, Y2. The SBCC was represented by Y1 and Y2. Y1 is the normalized construction cost ($\$/ft^2$), Y2 is the cost overrun (final construction cost / budget construction cost).

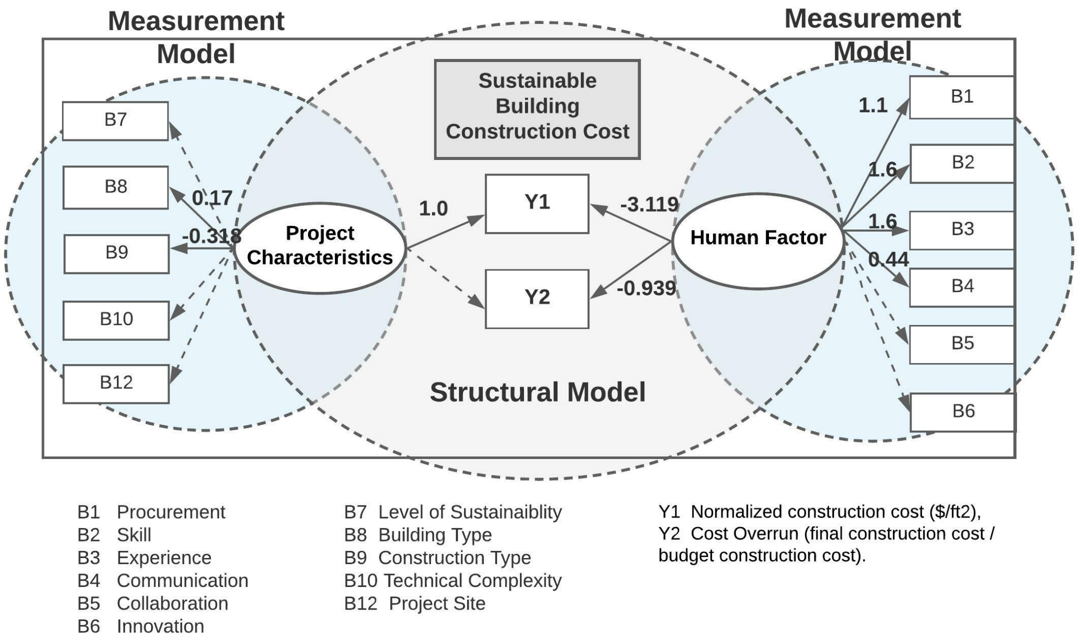


Figure 6.6 Final SEM model

Moreover, illustrated by each arrow (refer to Figure 6.6) is a coefficient that shows the level of influence in each causal relationship. The coefficient is calculated using Maximum Likelihood Estimation (MLE), based on the covariance matrix. It is interpreted and explained in Section 6.4.5. In general, a path coefficient is interpreted exactly as a regression coefficient, which is widely used to explain the level of influence. In addition, Figure 6.6 uses dashed lines to illustrate the causal relation with a low level of confidence and does not show the coefficient value. Table 6.11 and Table 6.12 show the statistical values of the measurement and structural components of SEM, including the measurement errors and confidence levels. The explanations of Table 6.11 and Table 6.12 are included in section 6.4.5 and section 6.4.6.

6.3.4 SEM fitness (GOF) and negative variance (Haywood case)

Five common model fit indices were used to test the fitness of the proposed model. The indices are the chi-square ratio (x2/df), root mean square error of approximation (RMSEA), p of close fit (pclose), comparative fit index (CFI), and Tucker-Lewis Index (TLI). The models with at least four fit indices meeting the requirements were accepted in this study (Kline, 2015a). Table 6.10 lists the test value and acceptable threshold for each statistic used.

Table 6.10 Model test and indices value

Fit Statistic	Test Value	Acceptable Threshold
chi-square	0.153	p > 0.05
RMSEA	0.05	< 0.1
pclose	0.223	p > 0.05
CFI	0.956	> 0.9
TLI	0.923	> 0.9

To accept models with a chi-square test, they must have a p value > 0.05 since the significance of a chi-square test is to indicate a poor fit of the model. In the initial model fitness test, the p value is 0.153, which is higher than 0.05, thus the model seems acceptable. The lowest possible RMSEA is 0. Values < 0.5 are considered indicative of a close model fit, and values up to 0.08 are acceptable (MacCallum, et al., 1996). The pclose is a test of whether the model departs significantly from one that is a close fit to the data (i.e., RMSEA < or = 0.05). In this test, RMSEA is less than 0.05, and the pclose is not significant (p > 0.05). Both findings indicate a close model fit to the data. The CFI and TLI are both incremental fit indices. Values > 0.95 for these indices indicate a very good model fit (Schumacker & Lomax, 2004). Values of 0.90 or above are considered an acceptable model fit (Pituch & Stevens, 2016). In this test, CFI (0.956) and TLI (0.923) are larger than 0.90;

both indicate an acceptable model fit. In addition to validating the acceptance of the proposed model, the author also examined the coefficient value to ensure there was no negative variance (Haywood case) estimated, hence there is no need to respecify the model.

6.3.5 Relationship between project characteristics and the sustainable building construction cost

As shown in Table 6.11, in the structural components, (**H2b**), the project characteristics positively affected the "unit cost" (Y1, standardized coefficient = 1.00, $p < 0.001$), while project characteristics do not have a statistically significant association with "cost overrun" (Y2, standardized coefficient = -0.016, $p > 0.005$). In the measurement component, the project characteristics are influenced positively by "**building type**" (B8, standardized coefficient = 0.017, $p < 0.005$) and negatively by "**construction type**" (B9, standardized coefficient = -0.318, $p < 0.005$). "Level of sustainability" (B7, standardized coefficient = 0.018, $p > 0.005$), "technical complexity" (B10, standardized coefficient = -0.01, $p > 0.005$), and "project location" (B12, standardized coefficient = -0.015, $p > 0.005$) do not have a significant influence on the construction cost.

Table 6.11 Estimation of relationship between the construction cost and project characteristics

Standarized	**Structural Component**		**Measurement Component**				
Endogenous variables	Unit Cost (Y1)	Cost Overun (Y2)	Project Characteristics				
Observed variables			B7	B8	B9	B10	B12
Coef	1.00	-0.016	0.018	0.017	-0.318	-0.010	-0.015

Std. Err	1.00	0.0058	0.14	0.006	0.008	0.009	0.008
P	0.00	0.78	0.03	0.004	0.00	0.31	0.008

This finding is different from the widely populated perception that building complexity is deterministic to the sustainable building construction cost. The rationale of such results can be explained by the similarities of technical difficulty among the studied projects. First, there is not much variation in technical difficulties among the studied projects. Most of the studied cases are federal office buildings owned by one federal agency, and the program and functional requirements of the buildings are similar, thus the technical complexity is not a characteristic that can differentiate projects. Second, among the different building types, the same sets of design and construction are required based on safety requirements, which make different building types owned by agency A more similar to each other than their counterparts owned by private developers. For example, both studied office buildings and port of entry buildings require a blast-resistant building envelope, which is different from conventional office buildings. Therefore, retrofitting an existing office building to become blast-resistant has become the primary technical difficulty across different building types.

The insignificant causal relationship between the LOS and the construction cost is not contrary to the widely accepted observation: there is a correlation between sustainability and the construction cost. The correlation demonstrates that two items typically occur together in a consistent pattern, while the two items do not necessarily have a causal relation. For instance, there is correlation between ice cream sales and sunglasses sold. They don't cause the sales of each other, but there is a consistent underlying factor that causes both events to occur.

The common believe is that the level of sustainability adds to the construction cost through contributing to the technical complexity, which leads to longer construction times, higher labor costs, and higher material costs. Since the findings show no causal relation between technical complexity and the construction cost in studied cases, therefore the causal effect of LOS and the construction cost cannot be established. Such conclusion is in align with the regression model analysis from Section 5.2. Consequently, such findings bring up the question: what is the underlying factor causes the sustainability and construction cost to be correlated then? Author attempted to provide the interpretation based on the knowledge of studied cases and years' experience working on LEED certified projects. The negative relation between the construction type (new construction vs renovation) and construction cost in the studied cases can be used to explain the correlation between level of sustainability achieved in the projects and the total construction cost: Majority of the studied cases are renovation projects. A renovation project has more uncertainty and risk due to the unknown condition of the existing building. Risk and uncertainty in construction projects often lead to schedule delays and cost overrun. The higher the level of sustainability the renovation project attempt to achieve, the higher the risk and uncertainty, the higher the possibility of cost and schedule overrun that leads to higher final total construction cost. This phenomenon can explain the negative correlation between project characteristic and construction cost. As for why there is no causal relation, the uncertainty and risk inherited in renovation projects are mostly non sustainability related or specific. The incomplete documentation and unknow condition are the cause of risk. For example, the original construction documents of existing building that is more than 60 years old did not reflect the building existing condition, and the documents for multiple renovations the original building has undergone is often incomplete. Designing based on incomplete information has the risks regardless the building's sustainability goal.

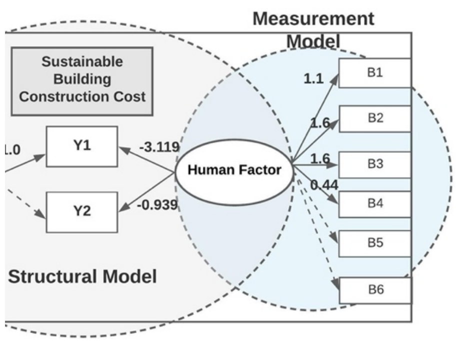
6.3.6 Relationship between the project's project team characteristics and the sustainable building construction cost

As shown in Table 6.12, in the structural component, (**H2a**), the project team characteristics is negatively effect the "unit cost" (Y1, standardized coefficient = -3.119, $p < 0.005$) and also negatively effect "cost overrun" (Y2, standardized coefficient = -0.939, $p < 0.005$). In the measurement component, (**H2c-H2h),** the project team characteristics are influenced positively by "procurement type" (B1, standardized coefficient = 1.1, $p < 0.005$), positively by "team skill" (B2, standardized coefficient = 1.56, $p < 0.005$), positively by "team experience" (B3, standardized coefficient = 1.63, $p < 0.005$), and positively by "team communication" (B4, standardized coefficient = 0.44, $p < 0.005$). However, "team collaboration" (B5, standardized coefficient = -0.939, $p > 0.005$) and "team innovation" (B6, standardized coefficient = 0.45, $p > 0.005$) were not shown to have a statistically significant association with the cost.

Table 6.12 Estimation of relationship between the construction cost and project team characteristics

Standarized	**Structural Component**		**Measurement Component**					
Exogenous variables	Unit Cost (Y1)	Cost Overun (Y2)	Project team characteristics					
Observed variables			B1	B2	B3	B4	B5	B6

Coef	-3.119	-0.939	1.1	1.60	1.61	0.44	0.44	0.44
Std. Err	3.365	0.139	1.3	0.03	0.31	0.35	0.64	0.49
P	0.0035	0.004	0.000	0.000	0.000	0.000	0.011	0.008



Considering the data collected for the study and the variables selected to measure the project team characteristics and cost, a possible interpretation of the results is described as follows: The higher the level of team skill (B2) and team experience (B3), the lower the risk of cost overrun, hence the lower the final construction cost for sustainable building, which makes sustainable building more comparable to conventional building in terms of unit cost (even lower than that of the conventional building). When researcher examined project team make-up of the studied projects. Those design-built teams who worked on the project with unit costs that were comparable to conventional building and without cost overrun are all in the top five of ENR rankings (Top Green Design Firm, Top Green Contractor), as leading experts in sustainable building design and construction firms.

For example, Arup is listed as number three in the top 100 green buildings design firms (2020) (Engineering News-Record, 2020) , and Hensel Phelps listed as number five in the top 100 green building contractors (2020) (ENR, 2020). Both firms have more than 10 projects together included in the studied samples, and most of those projects are LEED Platinum. The procurement type is closely related to the qualification of the firms, which is often measured by skill and experience, explaining why procurement is also positively related to the construction cost and closely correlated to team skill and experience.

Compared to team skill and experience, team communication (B4) has a less influence on the construction cost. Here, communication is measured by communication channels, and a positive impact means fewer communication channels. This finding is different from the widely accepted concept of more communication being better. On the contrary, excessive communication and communication channels can cause misinterpretation of information. What is needed is effective and accurate communication, rather than the frequency and volume of the communication. More skilled and experienced project teams may need less communication when their communication and coordination is effective. Such results confirmed several previous studies' findings. For example, Cho et al., (2009) found that a high level of communication among project team members was actually associated with a cost overrun and schedule overrun.

Overall, the effects of project team characteristics variables can be interpreted as follows: the **higher the level of skill** sets of a project team, **the more experience the project team** has with sustainable buildings and the **fewer communication channels** there are, the **lower the construction cost** caused by the high level of sustainability the project achieved. For example, to achieve a LEED Platinum certification level, a skilled, experienced team with efficient communication can reduce the risk of a cost overrun and schedule delays, consequently reducing the added construction costs. Such findings are in line with the impact of project team characteristics on conventional construction costs.

6.4 Data Analysis Results Discussion

There is a wide perception of sustainable building being expensive, and previous studies also showed sustainable building as having a higher construction cost compared to conventional building. However, the correlation between sustainability and the added construction cost is different from the causal effect between those two. There is a large body of sustainable building construction cost studies based on survey data, but analysis based on actual building construction costs is limited.

6.4.1 Data analysis result summary

The data analysis includes 72 GSA LEED certified buildings. Two regression model examine (i) the relation between level of sustainability achieved and total construction cost, (ii) the impact of soft cost and hard cost to total construction cost. The SEM examine the overall relationship between project characteristics and construction costs, and the relationship between project team characteristics and construction costs. This study deduced the overall causal relationship and level of influence among five project characteristics, six project team characteristics, and sustainable building construction costs.

The findings from the data analysis can be differentiate from the previous studies in three perspectives. ***First*** is whether the technical complexity is a significant cost driver to sustainable building construction cost. As previous studies showed, the sustainable building construction cost risk is mostly influenced by project scope, building complexity, and quality of design, as expected by the sustainable building rating tools to satisfy certification requirements. Therefore, the previous focus on sustainable construction cost studies have been related to technical complexity and project scope. From this dissertation study analysis, technical complexity is not shown as a significant factor to the final construction cost. Instead, a project team's skill and experience are the most influential and determining factors that drove the cost of sustainable building because the construction cost risk can be mediated and moderated by the project team's skill and experience. The higher the project team's skill and the more experienced the project team is in sustainable building design, the better the team can mitigate potential risks and uncertainty during the construction phase, hence reducing the risk of a cost overrun and/or schedule overrun. Overall, a project team's skill and experience can help to reduce the added construction costs of sustainable building.

Second is the importance of soft cost, that is closely related to the project team skill and experiences. Even though the soft costs associated with project team characteristics (paid to the project team) are a small portion of the total construction cost (less than 10%), they bear an important impact on the total project construction cost. Withing the soft cost, as demonstrated in the hypothesis (H1b) testing results, design fee is not only significant related to the final total construction cost, also its coefficient (0.906) is very close to hard cost (0.993). Such findings is aligned with the MacLeamy effort curve (refer to Chapter 1): the most important decisions related to cost and cost risk are decided in the early design phase. Consequently, we can speculate that investigate more in the early design phase and focus on the finding qualified design team can be equally effective as hiring qualified contractors in terms of controlling the construction cost.

Third is the dominating impact of project team skill and experience among studied project team characteristics. Unlike previous studies, team collaboration and team's innovation were not found influential to the construction cost. This finding from SEM seems counterintuitive to common perception and study results, therefore, the in-depth case studies are conducted to further understand why the innovation and collaboration are not influential, and in what mechanism the project design team's skill and experience direct contribute to the final construction cost of sustainable buildings.

To summarize, the findings listed above demonstrate the deterministic importance of skill and experience of project design team, that has been traditionally less understood and studied.

6.4.2 SEM Limitations

There are three limitations of this study that need to be mentioned. The first limitation is related to general limitations of the SEM method. Since SEM is a collection of statistical techniques—including correlation, covariance analysis, and factor analysis—there is no consensus on the definition of the quality of the SEM, despite there being a large body of literature and research on SEM (Vinodh & Joy, 2012). The second limitation is related to the projects team included in the study. Most construction costs were obtained from one federal agency. Becoming the contractor who bids and works on these types of federal projects requires a high security clearance. Therefore, the qualified companies are limited compared to firms who work on private sector projects. Consequently, the results of the project team characteristics analysis can not be generalized to describe all sustainable projects. The third limitation is associated with the building types included in the study. Due to using the same data source, the building types are limited and do not cover a whole range of the building's projects, which causes the project characteristics to have limited representation.

6.5 Chapter Summary

Chapter 6 presents the Phase 3 quantitative analysis results from regression models and SEM analysis. Ten hypotheses have been tested and the results are listed below.

Table 6.13 Hypothesis Testing Results

H #	Description	Results
H1a	There is no correlation between the construction cost and the level of sustainability	Inconclusive
H1b	The primary components contributing to the higher cost of SBs are derived from the hard costs.	Reject
H2a	The project team characteristics has negative effect on the final SBCC.	Accept
H2b	The projects characteristic has significant effect on the final SBCC.	Accept
H2c	The procurement method has positive relation to project team characteristics.	Accept
H2d	The skill level of project team in design has positive relation to project team characteristics.	Accept
H2e	The experience level of the project team in design has positive relation to project team characteristics.	Accept
H2f	The communication within the project team in design has positive relation to project team characteristics.	Accept
H2g	The collaboration within the project team in design has positive relation to project team characteristics.	Reject
H2h	The motivation to innovate of the project team in design has positive relation to project team characteristics.	Reject

The results first proved the importance of soft cost and project team characteristics: (a) soft cost is equally important as hard cost in the influence on the total project construction cost, (b) project team characteristics is more influential than the project characteristic to the total project construction cost, (c) within the project team characteristics, project team skills and experience are the dominating variables that determine the impact of project team characteristics to total project construction cost. Meanwhile, several statistical results are not in align with the common perceptions: (a) communication only show statistically insignificant positive relation to total project cost through the contribution to the project team characteristics; (b) collaboration does not show statistically significant positive relation to total project cost through the contribution to the project team characteristics; (c) motivation to innovate does not show statistically significant positive relation to total project cost through the contribution to the project team characteristics. Such discovery provided the direction to the researcher to conduct Phase Four research, case studies, to further explore and causes and understand the reason of those misalignment. In the following chapter, Chapter 7, the results of case studies are presented.

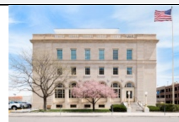
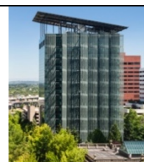
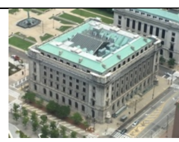
Chapter 7 Comparative Case Studies Findings

To further validate and interpretate the regression and SEM analysis results, in the qualitative phase of this research, three case studies (projects) were studied. The research questions addressed in the qualitative phase are how team skill and team experience have impact on the construction cost. Team communication, collaboration and innovation are also examined to understand why and whether they are less relevant to construction cost as suggested from the previous statistical analysis. Project statement, project presentation, project award submission materials of the three case projects are found and downloaded from variety sources including online resources.

7.1 Comparative Analysis and General GSA Practice

Three project and project team are selected as exemplary with successful sustainability achievement. The three cases are Wayne Aspinall Federal Building, Edith Green Wendell Wayatt Federal building, The Howard M. Metzenbaum Courthouse, together they offer insights on a range of project characteristics, design strategies, and process that were used by the teams to achieve aspirational performance goals. The range of selected projects allow the researcher looked into the project team characteristics' influence in a variety of contexts: a historic preservation with net-zero energy goals in Colorado, the renovation and expansion of an urban high-rise office building in Portland, and renovation project as first 40 GSA LEED certified building. When documenting project process and team characteristic, a comparative case-study strategy is effective, therefore a consistent format is employed in this Chapter to explain the findings. Table 1 include the comparison of the primary project characteristics and information of the three studied cases.

Table 7.1 Comparative table of studied projects

Project name		**Overview**	**Cost**	**Level of Sustainability**	**Location**
Wayne Aspinall Federal Building (WAF)		3 story 41,562 sf 2013 completion	\$15,000,000 \$361/ft^2 (\$508/ft^2)*	81/110 LEED Platinum Net Zero Energy	Grand Junction, Colorado
Edith Green Wendell Wayatt Federal building (EGWW)		18 story 512,474 sf 2013 completion	\$141,500,000 \$276/ft^2 (\$388/ft^2)*	84/110 LEED Platinum	Portland, Oregon.
The Howard M. Metzenbaum Courthouse (HMM)		5 story 236,632 sf 2005 completion	\$44,600,00 \$189//ft^2 (\$392/ft^2)*	47/110 LEED Certified	Cleveland, Ohio

*represent the conventional building cost at similar size and type and location.

If counting 5% annual inflation rate, then the "current cost" of three case projects are \$508/ ft^2, \$388/ ft^2, and \$393/ ft^2 respectively. That is still lower than average construction cost of non-LEED building. As mentioned previously in Chapter 6, in 2021, the average construction cost of new mid-rise (non-LEED) office building is \$562/ ft^2, new high-rise office building is \$779/ ft^2, average full renovation project construction cost is \$450/ ft^2 and \$623/ ft^2 for mid-rise and high-rise office building respectively.

Prior to the American Recovery and Reinvestment Act of 2009 (ARRA) (DOE, 2009), the GSA had very limited experience with design-build project delivery, but several GSA regions had been studying the potential use of alternative delivery types that were more integrated than the conventional design-bid-build (R. Cheng, 2015). ARRA was signed into law by President Obama on February 2009, and last till 2014. The goal of ARRA is to jumpstart the economy that hugely impacted by the recession, to create or save millions of jobs. Also, ARRA stipulated the funded projects need to meet the stringent energy and water conservation requirements of the Energy Independence and Security Act (EISA) at that time. EISA was signed by President Bush on December 2007. The aims of EISA included increasing the efficiency of buildings (EPA, 2007).

The context of the ARRA with its short time frames and aspirational goals for economic stimulus and high-performance buildings provided ideal conditions for testing the use of more collaborative delivery types, such as design-build (DB) or integrated project delivery (IPD) (Cheng, 2015). Even though DB project delivery method as collaborative methods is new to GSA at that time, however, DB method is a well-established method in private sector. Design-Built Institute of America (DBIA) was founded in 1993, since 2005, DB has steadily gain ground in residential and commercial buildings, both private and public sectors (Park & Kwak, 2017). Because of the unfamiliarity with DB as an institution, at the beginning, the GSA selection process and policies w were not well aligned for this type of project delivery. However, these difficulties were relatively easy to overcome due to the extensive experience with DB held by some GSA team members, partner architects, and contractors (R. Cheng, 2015).

Compared to DB, IPD was a newer delivery type; fewer people had experience with it, the lack of established procedure created the flexibility for the project team. In the following section, in Wendell Wyatt Federal Building (EGWW) project, the project team developed a customized delivery method based on IPD principles. Such customized delivery method helped the project team not only met with cost budget constraints, also helped to achieve an unprecedent energy performance goal. For all three projects, the adaptation of standard GSA practices to these delivery types required additional time investment and support at the design phase, and most important decision were made during the planning and design phase as well.

7.2 Case One- The Wayne Aspinall Federal Building

The Wayne Aspinall Federal Building (WAFB) was built in 1918 in Grand Junction, Colorado. It is a 3-story office building with gross area of 41,562 sf. Its original function was post office and courthouse; a large extension was added to the east side of the original building in 1938 for office space. The original design and construction did not include HVAC system, an HVAC system was added in the 1960s, along the upgrading electrical system. Acoustic ceiling tiles were also added to improve the sound quality, as well as conceal the HVAC duct work. The original lighting fixture was replaced with ceiling-mounted fixtures and wall sconces as well (R. Cheng et al., 2014). Since then, there has been no major repair, renovation, or upgrades. The building was listed on the National Register of Historic Places in 1980 (General Service Adminstration, 2014).

In 2010, GSA considered disposing the building due to its extensive repair and renovation needs, at that time GSA could not hope to cover the potential cost from existing or expected federal funding appropriations. Majority building system and components had reached their end of useful life, and needed major updates and repair, meanwhile the poor ventilation and indoor air quality needed to be addressed as well. Disposal of the existing building was avoided when the building received funding from the ARRA from the congress to undergo a major renovation. GSA set up an unprecedented extensive renovation plan combining net zero energy goal and historic renovation goal. The renovation was completed in 2013, and achieved LEED platinum certification, score of 81/110. Total construction cost is about 15 millions, and the unit cost is $361/sf.

7.2.1 Technical Complexity

Renovation while maintain operation

An overarching challenge was to undertake the construction in an occupied building, where construction crews could encounter unforeseen conditions and risks. Such uncertainty can cause construction delay that leads to construction cost increase. There were situations when the project energy efficiency goal did not align with the tenants' preference. For instance, project team proposed to consolidating copy rooms and server rooms to reduce the energy load of the building, however, the existing tenants preferred to keep them in separated spaces. The project team were able to persuade tenants on consolidated copy rooms, but, due to the security concern, the idea of consolidation of server rooms were abandoned.

Aggressive energy goal vs historical preservation

The most controversial design elements to the historic reviewed board was the roof-mounted PV array (refer to Figure 7.1). The NHPA Section 106, the SHPO's initial review critiqued the appearance of the large PV panels in the view of buildings' front façade. It was said as "destroy historic…features and spatial relationship that characterized the property”. The NHPA reviewers requested that the project team reduce or remove the PV canopy from the building.

Figure 7.1 Roof mounted solar panel

Reducing the PV size or removing PV canopy would have detrimental effect on meeting net zero energy goal, so the project team had to come up with alternative solution: concurrently with increased insulation in the building envelope, the project increased energy efficiency through geothermal system. The geothermal heat exchange systems are about 45% more efficient than a typical HVAC system, and in this project the vertical well is about 475 foot deep. By combining super-insulated building envelope and more efficient HVAC system, the project design team were able to reduce heating and cooling demand, consequently the size of PV panel while meeting the net zero energy goal. Geothermal heat exchange system is a relative advanced building system compared to conventional HVAC system, the related technical complexity was mediated by the project design team who have had previous experience implementing similar system in other projects. Therefore, the design, construction and installation of such system were able to be controlled within the original budget.

7.2.2 Sustainability

GSA set up high goal for this historical preservation project: (1) realization of net zero energy (aligning with government requirement for net zero and energy independence by 2030). (2) achieve LEED Platinum certification, (3) improve indoor environmental quality and thermal comfort, (4) reduce water use by 40%.

7.2.3 Procurement and Contract

GSA used design-build (DB) contract, the energy goal was outperform ASHRAE Standard 90.1 – 1999 by 30%, with the fully replacement of HVAC, electrical and plumbing system. The project budget was totaled $15 million [1]. Additional sustainability goal of the project includes reduce water use by 40%, achieved LEED Platinum certification, realizing net zero energy goal, use sustainable construction practices. The advantage of DB contract is that it can bring project team (design and construction) together at the outset of the project.

WAFB followed a two-step procurement process, combining qualification-based selection and best value selection (refer to Chapter 4.3.2). It first requested qualification from potential team, then issued a request for proposal. The proposal phase required bidders to address minimum performance criteria and encouraged to bidder to provide innovative design solutions. Since the bidder constitute design team and contractors, hence in their proposal, they can propose an integrative way to mitigate the risk, consequently, maintain the pricing through design development based on the contract documents through construction.

One unique thing about WAFB contract is that project team's proposal was incorporated into the final contract, even the PowerPoint presentation delivered by the team during the interview became a part of the construction documentation for the project. Such highly integrated manner was thought to help the project to mitigate the risk that can be encountered during the construction.

7.2.4 Project team characteristics

Team skill and experience

Selecting a team for historical renovation projects with net zero energy goal is the most important upfront decision. At the end, GSA first select Jacobs Technology as the Construction Manager (CMc), then GSA implemented best-value-selection process on this project (applied to most ARRA projects), the best-value-selection process allows GSA to select team based on a combination of past performance, technical capacity, and qualification that based on skills and experience.

Westlake Reed Leskosky (WRL, later acquired by DLR) provided MEP engineering, interior design, historical preservation, and LEED consulting service. WRL was funded in 1905 based at Cleveland. Since 1997 WRL redefined and narrowed its focus on building types, historical preservation was one of four focus areas of their practice. In 2016 WRL ranked number 7 by "Architect" magazine in Top 50 firms (Cleveland.com, 2019). Architect magazine is the official publication published by the American Institute of Architects since before World War I. Its ranking is based on evaluation on architecture firms' businesses operation, sustainability practice and design excellence. Its expertise in design was also supported by the strong commitment to research, for example, in 2013, 60% of firm profits went back into research (ARCHITECT, 2016) . Such investment helped to build the firms' technical strength, that lead to the success of projects like HMM and Wayne N. Aspinall Federal Building. The Beck Group was the general contractor and architect of record, based in Texas. Beck is a design- and- construction firm. It was ranked 38th (in 2019) and 34th (in 2018) green contractors by ENR (ENR, 2019). In addition, it was rated US best managed company in 2021(BECK, 2021). Subcontractors for Beck were selected using conventional methods.

Both Beck and WRL are interdisciplinary firms with established culture of working collaboratively between disciplines. Even though those two firms did not have working relation prior to this project, their internal organizational culture were compatible and needed very little alignment or adjustment. This also demonstrate the skills and experience are underlying factor that can lead to good communication and collaboration because based on the previous experience, the firms understood what can be the most effective communication method, and they know what to do to create a collaborative team. In addition, team members noted that they believed that others would performs as promised and that each team member or firm would hold themselves responsible, such high level trust was not based on previous working relation, rather, it was derived from the evaluation of members and firms' skill and experience.

Team collaboration and communication

WAFB has a normal design-build contract and team organization, as illustrated in Figure 7.2, the main collaboration and communication happen between WRL and Beck since majority team members were drawn from those two firms. Prior to working together in the newly established project team, the two firms already had well-established method of integration due to its multidisciplinary nature. Individual team members were already well versed in cross-disciplinary collaboration within their own firms.

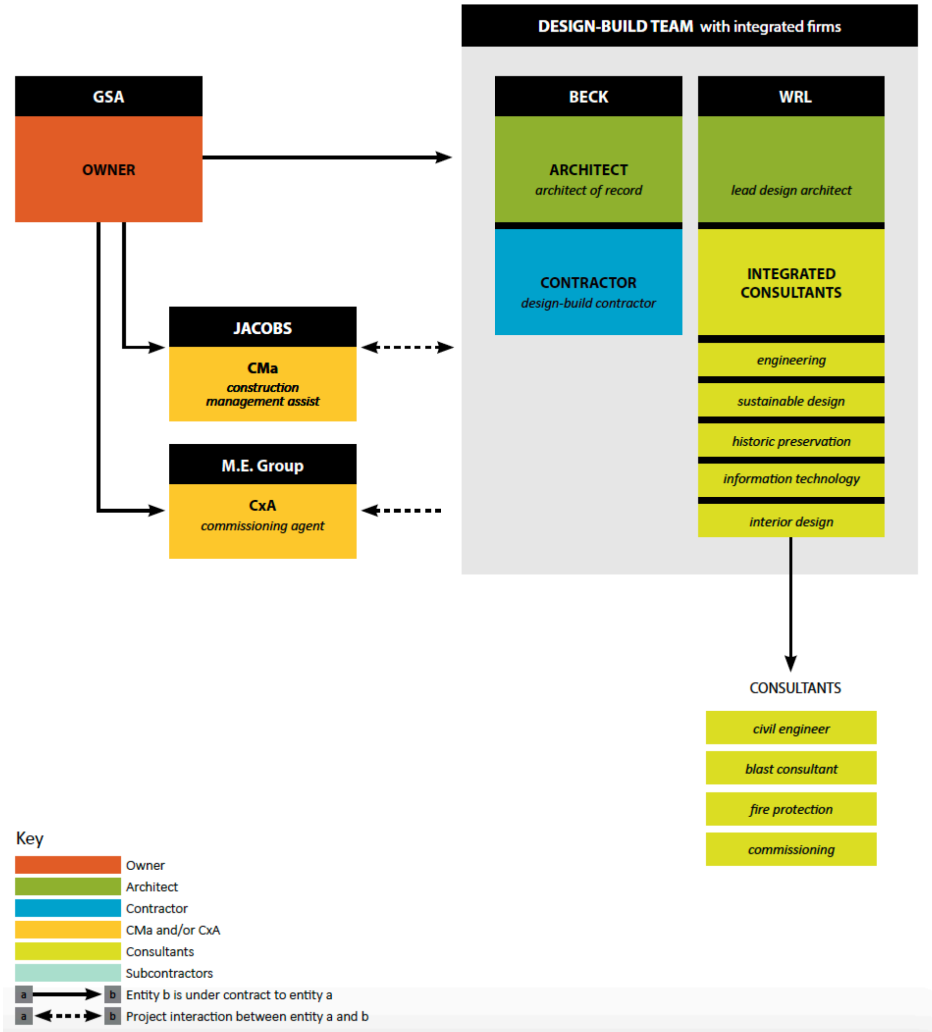


Figure 7.2 Team Organization

In the early design phase, the team collaborated remotely, later in construction phase, the core team members from both WRL and Beck were located on-site, in the basement of the building, with others travelling to the site regularly. GSA project manager was also co-located in the same place. “The team noted the increase in direct working relationships and the ability to get to know each other on a personal basis strengthened communication and trust among the core team members.” The team believe the co-location strategy helped support communication, collaboration and management.

Innovation

The first innovation of this project is the way and method project team used to manage the risk and uncertainty. First, to manage the risk form SHPO historic review process, the project team reached out to SHOP and with them together developed a strategy facilitate the historic review process. This way, project team was able to move incremental progress and reduced the risk to the pieces can be managed. Second, to manage the uncertainty derived from the fact the building was kept operation during the construction, the project team used physical mock-ups to effectively communicate the design intent to the project manager from GSA, as well as to tenants. Mock-up the interior space renovation with intended layout and furnish, so everyone can review and understand the design ideas.

The second innovation is Building Information Model (BIM) and its utilization. BIM was employed as design, documentation, communication, management and collaboration tool throughout the design and construction to manage project complexities. And it was also employed to assist in design decision making related to the net zero energy performance goal. The project team developed a BIM execution plan at the beginning of the project to set up the procedures of developing BIM model, shared and updated the documents, and outlined each members' responsibility. BIM model was also linked to energy model early in the project. Regardless the perceived advantage of utilizing BIM in design-built projects, the actual benefits remain somewhat unclear. As one team member noted: "within the project team, we still have to communicate the information scope out to the subcontractors. That information can be related in different ways, but the content still needs to be developed to a level that somebody outside the team can understand." Such undefined the benefit from the innovation contribute to the explanation why innovation did not show significant impact on total construction cost.

7.2.5 Construction cost

This project had fixed price budget which was set the early stage. When project team making proposal to bid the project, the scope and schedule was taken into consideration. The GSA project manager noted that the fixed price was a clear motivator for the team " did not want to go back and ask for more money. We had a team that was very good identifying what we could do to make things cost effective." (Cheng et al. 2015). The procurement method employed, the selection criteria integrating qualification (design team skill and experience) and best value (design proposal) enabled GSA select a design team delivered a project design that meeting all energy performance goals within the allowable budget. This case study is a clear indication that skilled and experienced design team not only provided practical design solution, also were able to know what tool and methods can be used to facilitate communication and collaboration even during the construction phase.

7.3 Case Two- EDITH GREEN - WENDELL WYATT FEDERAL BUILDING

Edith Green Wendell Wayatt (EGWW) Federal building was built in 1974 in downtown Portland, Oregon. It is a 18-story office building with total gross area of 512,474 sf. The building received funding from the ARRA to undergo a major renovation. The project was completed in 2013.

7.3.1 Technical Complexity

Complete building envelope retrofit

Replacement of the existing pre-cast concrete cladding with a high-performance façade (refer to Figure 7.3). The façade system has integrated aluminum reflecting and shading elements that were designed to respond year-round variation of the sun angle. On the south, east and west side the new facade integrate the shading device to minimize the solar heat gain. On the south façade, the horizontal light shelf can reflect the light deeper into the office space, hence to decrease the demand for electrical lighting as well. The new secondly slanted roof was a new addition added on top of existing roof. It is covered by PV panel and supported by steel truss, so there is additional structural system added to support the PV panel. Recladding façade with sophisticated layered system has some contribution to the sustainability goal, however its contribution is very limited, mainly it is an added design feature since this project serve as a flagship example to demonstrate the design excellence.

Figure 7.3 building envelope renovation before (left image) and after (right image)

HVAC system retrofit: Radiant cooling system

Another major technical challenge is the installation of hydronic radiant ceiling with direct outside air system (DOAS). It was estimated to save 10% to 15% of total building energy use when compared to a variable air volume mechanical system (refer to Figure 7.4). Radiant cooling was a relatively new technology in the US, in order to manage the risk, the design team reallocated funds and designated a team member to work directly with the manufacturing facility.

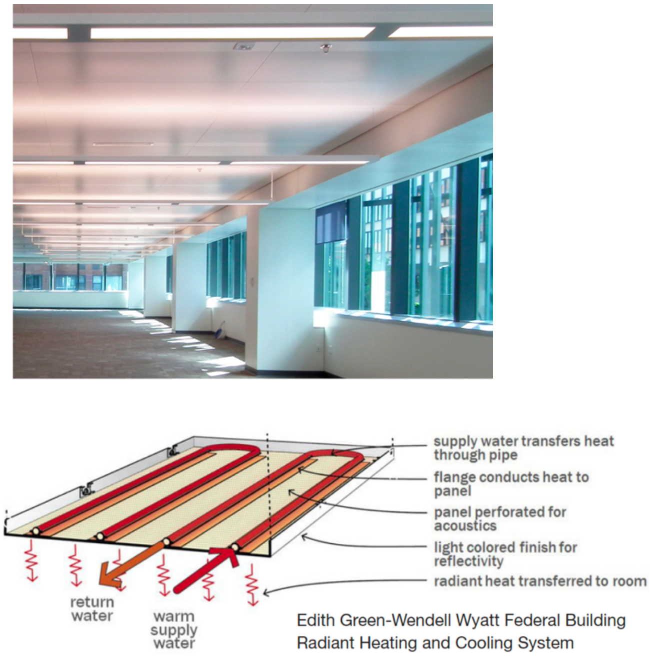


Figure 7.4 Radiant heating and cooling celling system (credit to SERA Architect)

7.3.2 Sustainability

EGWW is LEED platinum certified. Before the renovation, the energy use intensity of existing building is 75.5 kBtu/sf, after renovation the EUI is 29 kBtu/sf, that is 55% reduction from national average, compared to building of similar size and type (R. Cheng, 2015). As for the water conservation, EGWW achieved 60% water saving through strategies of incorporating both water-conservation plumbing fixture, water reuse and rainwater capture. One unique sustainable practice is worthy to be noted is about reduction of demolishing waste, hence contribute to material conservation. A subcontractor in charge of demolition was brought onto the project ream at the beginning of the design, that is quite unusual, the subcontractor together with the project members developed the demolition drawings and specs, and recycle and reuse strategies during the design phase. Such practice served two purposes: first is to help demolition contractor understood the projects' sustainability goals, second is to help the team to create a process with demolition contractor to track the material conservation goal (R. Cheng, 2015).

7.3.3 Procurement and Contract

Prior to getting funding from the ARRA, the GSA's Northwest/ Artic Region (region 10) hired SERA architects, for design services of this renovation project. The original contract is a traditional design-bid-build (DBB) delivery method. After obtaining approval for ARRA fund in April 2009, this project was required to be re-scoped to align with the high-performance green building goals, that add a very different set to goals and technical specifications. In addition, ARRA fund need to be committed no later than September 2010 and spent before September 2015. Such defined funding requirement and timeframe became the driving force to switch from traditional DBB to a more integrative project-delivery method. After conducting market research, GSA determined that a general contractor/construction manager delivery method, which the GSA refers to as the construction manager as constructor (CMc), along with a guaranteed maximum price (GMP) contract type were most appropriate for the project scope and constraints—specifically, the securing of project funding by September 2010 [Cheng 2015]. The final delivery method of EGWW is construction manager (CMc) using guarantee maximum price (GMP). GMc was not addressed in federal rules before 2018, CMc/GMP is not currently addressed in federal rules, therefore, such type was authorized for use on EGWW as an exception (Cheng 2015). In addition, unlike a normal CMc delivery method, the significant variation is that the formation of design (architect and engineer) was very early (prior to the RFP). After getting the funding from ARRA, GSA decided to retain SERA as the architect of the project and engaged SERA in the request for proposal process. Among the reasons retaining SERA, one of them is related to SERA's expertise in high-performance green buildings and past experiences.

Two uniqueness about the procurement and contracting process are the primary contractor team selection and subcontractor selection. EWGG has invited all general contractors who had intent to compete the project to attend a high-performance green building re-scoping workshop. The final selection of the contractor was based on its technical capability, including past experience and key personnel's expertise and experience. The primary contractor was required to submit recommendations for their five first-tier subcontractors when compete, this was not usual for GSA project. Such process on one hand can help the project team and GSA management team to ensure the contractor team has the capacity to deliver the projects, on the other hand, bring subcontractor early onto the project can help to turn subcontractors to the co-owners of the project, so that they can be more involved in the value engineering process.

7.3.4 Project team characteristics

Team skill and experience

As mentioned above, SERA architect was retained for its expertise in high-performance building design. In 2010, the prominent architecture profession magazine, Architect, ranked SERA architects as the top 3 green design firm, followed by other large international firm, such as Cook+Fox, HOK and FXFOWLE. At that time, 60-79% projects in SERA are LEED projects. What is unique about SERA is that since 2008, it has been developing the firm's in-house Sustainability Resource Group (Architect Magazine, 2010), that comprised of experts in different disciplines, including mechanical engineer, façade engineer, daylight and lighting designer in addition to architects (Architect Magazine, 2010). In this way, SERA has not only developed the expertise, also developed the collaborative mind-set, approach and culture for project. So, from this perspective, the skill includes effective communication and collaboration.

As for general contractor included in the design team, Howard S. Wright, has the experience mainly working within then western states of the United States. In 2008, it was ranked in the Top 100 Contractors by ENR, and it was acquired by Balfour Beaty in 2011. Howard S. Wright (HSW) had great experience in large and complicate projects, such as Century 21 Exposition and Space Needle in Seattle, a 138 ft tall observation tower, that currently is landmark building. Their experience and skill in dealing with complicate and non-precedence projects was main reason for GSA selected them as the general contractor.

Together the leading design team (SERA as executive architect) and general contractor (HSW) has combined skills and experience ranked very high.

Team collaboration and communication

Due to the local condition such as geographic location, owner/team issues, the GSA regional 10 has been developing its own CMc protocol to accommodate and guide the local practice. Such development and deviation from conventional CMc made the Region 10 CMc more similar to Integrated Project Delivery (IPD). The major modification in Region 10 CMc were listed below and all those were reflected in EGWW.

- GSA has on-site manager during the construction phase.

- The selection of major first-tier subcontractor prior to the design was developed
- Shared co-location facilities
- Use of BIM

As one GSA Project Executive said about EGWW, “Having on-site personnel, co-located with the team, has had a significant impact. This attribute may have had a greater impact than the contract form or type.” As illustrated in Figure 7.5, the project team worked under an integrated agreement in which way was similar to IPD.

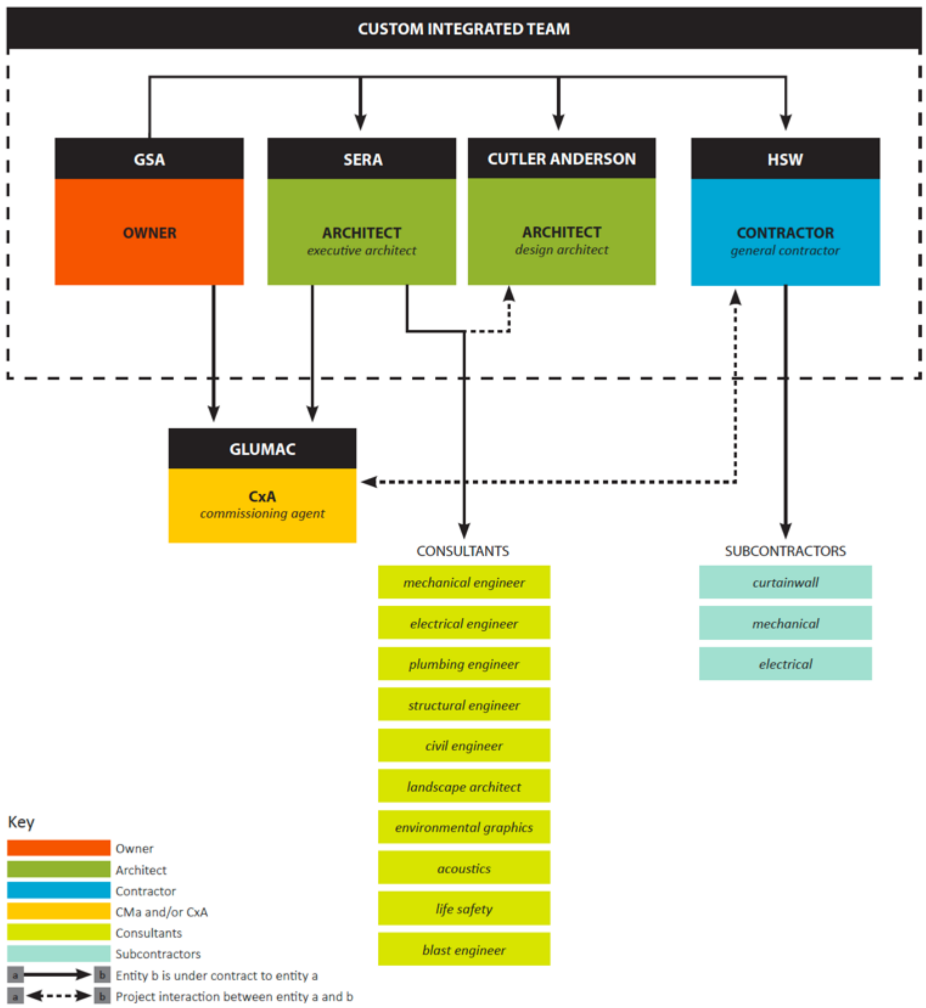


Figure 7.5 EGWW project team organization (R. Cheng, 2015)

Innovation - Radiant Panels

To find out why innovation does not have significant impact on construction cost, the researcher further investigated the statement from project team, including GSA program managers. One pattern merged through many project documents around the important leadership role GSA local program manager played to leading the effort for innovation, to some extend even **forcing the innovation upon project team.**

One great example is the design the installation of the radiant cooling and heating ceiling system in EGWW. Because this system was and still relative new to American market, the design team expressed concern about using such system. Besides the unfamiliar to such system, the lack of the air movement is another major concern. Using radiant system, it eliminates the fans found in traditional HVAC based on air, consequently the "flowing" air from traditional system. Although the radiant system provides a high level of thermal comfort and indoor air quality, it was predicted that occupants accustomed to noisily blown cool or warm air (as in traditional systems) would perceive a problem linking minimal air movement to a lack of cooling. One way this was corrected during the post-occupancy work was to adjust the range of temperature allowed to improve the balance between energy savings and occupant comfort [AIA Top Ten COTE]. One member from design team stated *"For me, it was unique to be in a position to see that my team was expressing a significant concern and having the owner in the group say, 'We understand. We think that the benefit is worth the risk.' Having that really clean and open dialogue. That's not your everyday life [in the building industry]."*

In this case, the innovation is drive by the determination of client, rather than project designer, or at minimal the client and project team play equally important role to implement the innovative solution. The skill and experience of project team outweigh the innovation since the project team in this case switch its role to be on the conservative side to make sure the design solution can be delivered. This is very different from conventional projects.

7.3.5 Construction cost

This project has GSF of 512,474 square feet, and construction cost is \$141.5 Million, the normalized cost is \$276/ft^2 . Two project specific characters contribute to the control and reduction of construction cost. The first is related to project contractual / team organization. The EGWW project organization is more similar to IPD over the conventional DB, therefore, the project budget and schedule was organized in a highly collaborative way since the project team share the profits and risks. While the GSA owner was the final decision-maker, the contingency was treated as a pool of money to be used to benefit the project and decisions for its use was shared. Particular savings were attributed to the way value engineering of the GMP budget was inclusive both prime and first-tier subcontractor. Such collaborative decision making, and contingency sharing mechanism was used to reduce project budget. As a full renovation projects, one of the biggest risk is the unforeseen condition of existing building, EGWW can take a team approach to decide how contingency would be used to address those unforeseen issues, because the integrated team setup.

The second is the use of Building Information Model (BIM). EGWW is among the earliest GSA project fully utilize BIM from design to construction. The project team was very innovative in its use of BIM by developing an information room (which they dubbed the iRoom), a combination of centrally managed BIM in a co-located office. From the early design phase, the team members including sub-contractors had access to each discipline's design via co-located BIM models on a shared serve in the iRoom. Such open access within team enable the project team for on-the fly coordination among disciplines, in addition, first-tier subcontractors were also co-located, so they can provide constructability reviewer during the design phase using the virtual model, to reduce the risks and mistakes that typically happen on the construction site. Such early trouble-shoot contribute to the reduction of cost as well. EGWW team was not only just using BIM for real-time coordination, they also developed a unique BIM process called "BIM Snapshots." Instead of structuring the delivery of drawing packages, following the conventional project process (SD, DD, etc), BIM Snapshots created drawing packages by capturing images at specific moments during design, after which the project design team printed drawing sets from the BIM model. And those BIM Snapshots were then aligned with the CMc's contingency strategy, made possible by the back-and-forth coordination between the CMc and the architect. The BIM Snapshots together with printed drawings were used by owners to validate the design intent and by CMc to solicit subcontracts. As illustrated in Figure 7.6, such approach allowed the project team and owner to prioritization within the design process, deferring non-critical portions of design to later phases. This helped maintain the aggressive schedule. The team estimates a $940,000 saving in project costs because of the reduction in the hours spent on design documentation – from a typical schedule of 53,000 hours over twenty-four months to 44,000 hours over fifteen months (R. Cheng, 2015).

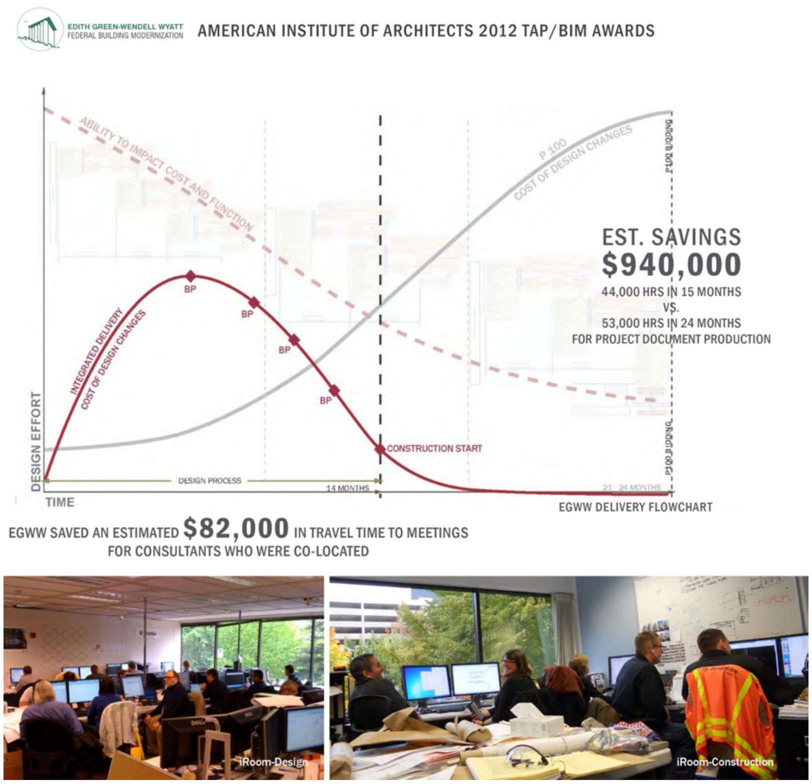


Figure 7.6 iRoom coordination and BIM saving (credit to AIA TAP 2012)

BIM models were also used to run clash detection by design team. The clash detection allowed coordination among multiple systems including structural and mechanical system. And the BIM clash detection and coordination enable 38% reduction in fabrication time by using mechanical systems “Modular Skids” prefabrication by providing against conventional on-site fabrication (AIA, 2012).

7.4 Case Three - Howard M. Metzenbaum US courthouse

The Howard M. Metzenbaum (HMM) US courthouse is five-story, 236,632 square feet, office building located in Cleveland, Ohio (GSA Region 5). It was built in 1910 as a courthouse and registered as Historic Place in 1974. HMM has undergone several major extension or renovations including adding HVAC system in 1960s along with upgraded electrical system. After the original tenants being relocate to the new U.S Courthouse, the Metzenbaum courthouse was vacant in year 2002. The tenant space alternation and building system modernization were done to backfill the Metzenbaum courthouse with new tenants. The complete renovation was completed in 2005 with the goal of historical preservation and energy efficiency upgrades. The renovation includes complete replacement of HVAC, electrical, fire/life safety, security, alarm, and communication systems. The project also converted the basement space occupied by the U.S. Marshals to parking. The original proposed budget was funded in year 2001 include the following: design ($ 2,301 thousand),construction ($ 24,817 thousand) , and management and inspection ($ 2,283 thousand) . The estimated total project cost was $ 29,401 thousand (Gernal Services Adminstration, 2002). The actual total construction cost provided by GSA was $ 44,600 thousand, the normalize unit cost is around $189/sf. Even though the final construction cost is almost double of the original budget, it is still substantially lower than most full-scale renovation projects. For this reason, HMM was selected to understand the underlying factors and reasons for the low cost.

7.4.1 Technical Complexity

Since the project was completed early with lower LEED certification requirement from GSA, the technical complexity of the modernization building system was not significant, the real challenged was induced by the conflicting needs of renovation/modernization with the preservation of the buildings' historical feature and significance. For example, after the construction team removed the drop ceilings that were built in around 1960s to contain the duct for air conditioning system, they discovered the original ceiling and ornate plasterwork (*HOWARD M. METZENBAUM U.S. COURTHOUSE*, n.d.). In order to reveal and the original historical ceilings and plaster ornament, the project design team came up with the solution putting mechanical chases and risers into the no longer in used chimneys. Because of the historical place status, a substantial portion of construction cost are dedicated to historical preservation or restoration. For example, the project reinstalled restored original 35 murals by 19th century American artist, Francis Davis Millet (DLG Group, n.d.). And most cost associated with historical preservation or restoration are not directly related to sustainability or energy efficiency.

As for the building system complexity, most upgraded HVAC, electrical and plumbing system are the same as used in new construction, and with no substantially higher cost. One advanced mechanical system bear with addition cost worthy to be mentioned is the demand control ventilation system (refer to Figure 7.7), that connected to the CO_2 sensors inside of the room, so the ventilation can provide higher indoor air quality by adjusting the outside air intake meanwhile preserve energy.

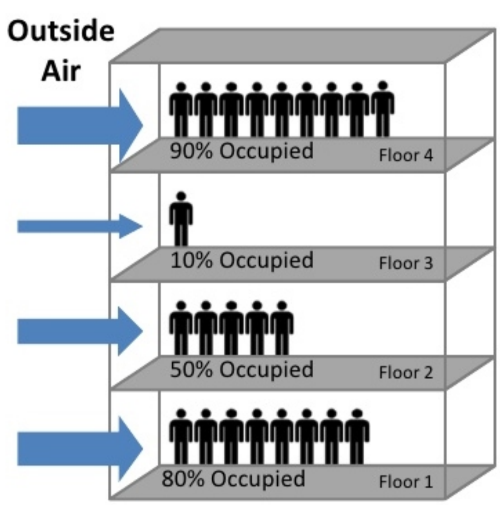


Figure 7.7 Diagram of demand control ventilation system

7.4.2 Sustainability

HMM was the first adaptative re-use project in the GSA portfolio to achieve LEED-NC certification, and it is also one of first 40 GSA LEED projects. Its LEED score is 44 out of 110. The actual energy use is 84 kBtu/sft, the water use is 2.14 gallon/sft

7.4.3 Procurement and Contract

HMM is DBB contract with construction manager (CMc). Dick Corporation was hired as the construction manager who is also general contractor.

7.4.4 Project team characteristics

Team skill and experience

Westlake Reed Leskosky (WRL, later acquired by DLR) was the leading design firm, provided MEP engineering, interior design, historical preservation, and LEED consulting service (refer to Case One). The construction manager and general contractor was Dick Corporation, a Pittsburgh based company. It was ranked the 345 among the top 400 international contractors, but it was ranked as 10th largest builder in the hotel market space (DCK, 2019). It was not within the rank of top green contractors. Compared other more high-ranking contractors with extensive experience in sustainable construction, Dick Corporation has more strength in multiple-family units and hotels. Together the leading design team and general contractor has combined skills and experience ranked high.

Team collaboration and communication

As illustrated in Figure 7.8, the project team organization is a conventional design-bid-build project. The design team and contractor had very limited interaction, the main communication was between owner (GSA) to design team, consultants, and contractors. The researcher was not able to find further details of collaboration and communication among the project team, therefore, it was assumed the level of collaboration and communication was average.

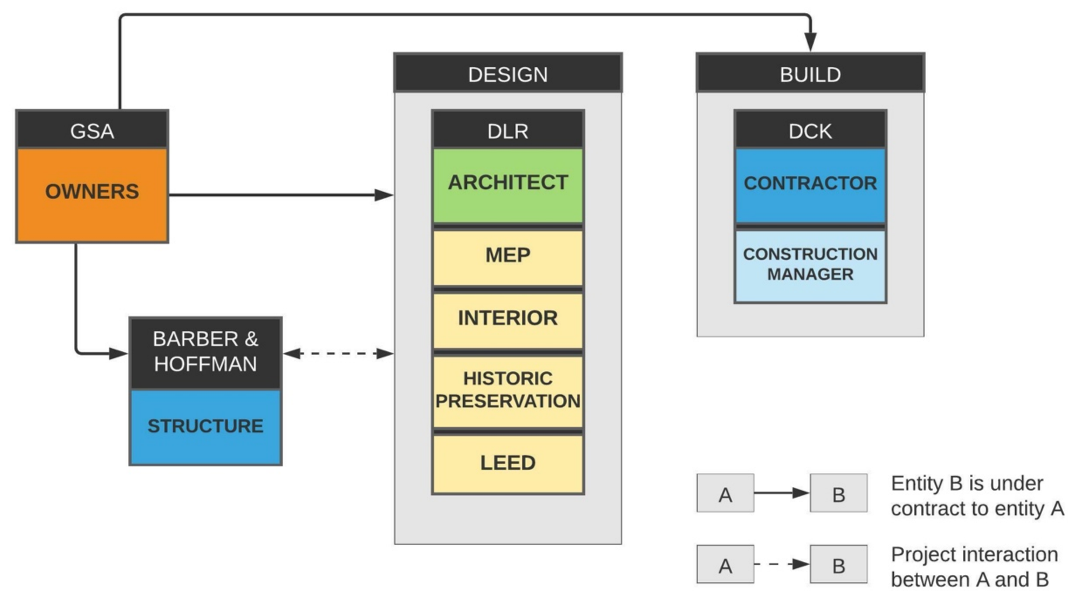


Figure 7.8 Team organization

Innovation – space alternation

The most design innovation is about key space alternation (refer to Figure 7.9). The design converted the previous courtyard (open to sky) to an atrium covered by glass skylight. Such space function change solved the circulation problem, increased security requirements, and allowed the historical corridor systems to be allocated to active tenant use (*HOWARD M. METZENBAUM U.S. COURTHOUSE*, n.d.). It was claimed by the project team that such light well dramatically reduced the building's energy use through reducing the demand for artificial lighting. However, to researcher's knowledge, there was no data found to support such claim.

Figure 7.9 Renovated courtyard/ atrium space (credit to library of congress)

7.4.5 Construction cost

This project has total construction cost of $44,600,000, normalized cost of $189//ft^2$. It was completed in 2005, when covert to net present value with 5% inflation rate, the cost is $393//ft^2$, that is higher than that of conventional building, $330//ft^2$. However, the majority of the construction cost are related to the space alteration, converting the open courtyard to the closed atrium space. The contribution of energy efficiency of such space alternation was not well documented, consequently the cost can not be completely tributed to the sustainability pursue. The initial budget for this project is $29,401,000, normalized cost of $116//ft^2$. The cost overrun is 63%. Since this project is among the first 40 GSA projects become LEED certified, therefore the cost overrun can be tributed the inexperience of project team to LEED system.

7.5 Discussion and Take-away

From the in-depth case studies, three important take-aways can be concluded: (a) the significance of project team's skill and experience were reflected in the success of project measured by the achieved level of sustainability while keeping the total construction cost within the budget, (b) collaboration and communication are predetermined by the procurement process and project delivery method, therefore their importance were not identified by the statistical analysis, (c) in studied cases, the technical complexity was derived from the challenge of meeting energy performance while preserve the historical significance of the existing building. The most difficult issues were not directly related to energy efficiency or sustainability, hence the increased cost. Table 7.2 listed the project team characteristics characteristics of the three case projects.

Table 7.2 Case projects' project team characteristics' comparison

Project name	**Procurement**	**Skill**	**Experience**	**Communication /Collaboration**	**Innovation**
WAF	DB	Experts	High	Excellent	Geothermal system/ building envelope
EGGW	CMc/ GMP	Experts	High	Excellent	Radiant ceiling
HMM	DBB (with CM)	Experts	High	Normal	Space alternation

7.5.1 Team skill and experience is key

For the projects with higher sustainability level and relative low cost, "**buying a high-performance team"** instead of buying a high-performance building is GSA's approach from the beginning. The high-performance team can assure the delivery a high-performance product, and finding the right people and team building is critical. Therefore, spending time in the planning is important and necessary. For example, Case 1 spent 4 months (02/2010-06/2010) in procurement phase, and 15 months on design (06/2010 – 09/2011). The procurement phase was compressed and GSA made decision early on to use a design-build project delivery method to renovate this historical building, therefore, GSA intentionally keep the procurement process interactive by inviting open dialogue with participating firms on how to best meet the net zero energy goal (Cheng et al. 2015). As described by a DB team member, "…with design-build, teams have to do a lot of work at the front end to even compete. Design-build teams that bring proposals to the GSA need to formulate a design that is progressed far enough along in terms of infrastructure, architecture, and cost.." Such level of design development at early planning stage is largely hinged on the skill and experience of design-build team. In both Case 1 and Case 2, the "right people" is identified as a key to the project team skill and experience. In Case 1, The GSA project manager noted that the fixed price was a clear motivator for the team, as quoted from the project manager: "We had a team that was very good identifying what we could do to make things cost effective." The skill and experience of the project team helped the team come up with practical design solution within the budget, that is both realistic and highly innovative. As for Case 3, the leading design firm, WRL has extensive experience and speciality in historical preservation that helped to balance the relatively inexperienced general contractor(in sustainable design). As pointed out in 2014 GSA report on net zero energy projects, assemble a team of dedicated members with the qualifications will assist in attaining the established targets, for both energy performance and cost budget targets. In all three studied cases, project team skill and experience are ranked high. WRL was the leading design firm for both case 1 and case 3, and WRL provided architectural design, interior design, MEP engineering, historical preservation, and LEED consultant service for both projects. WRL is a firm with expertise in historical preservation and strong focus on research-based design approach, it was ranked within the top 10 firms by peer institutions nationally. The leading design firm, SERA was ranked top 3 nationally as green design firm, such recognition is reflected in their skills and experience in sustainable building design and construction. Both WRL and SERA are interdisciplinary firms with experts in architecture, mechanical engineering, façade engineering and others, such interdisciplinary firm cultural and mind-set play critical role leading the project teams overcome the difficulties derived from the higher energy performance goal, short project timeline and fixed budget.

The findings of importance a high-performance team validate the concept of effort curve proposed by Paulson and further developed by MacLeamy. As Paulson pointed out the decision and commitments made during the early phases of project by the design team have orders of magnitude greater influence on what later expenditures will actually be. This is approved by the high coefficient of soft cost that indicating the design team's input. Due to the specific funding mechanism, GSA projects has a constrained the budget and schedule, in order to ensure the delivery of the project at required LEED certification level, the owner paid lots of attention during the project planning and procurement stage, GSA did not use low-bid method, and also did not try to cut down the design cost, instead, the focus was on best value and team's performance. This approved Paulson's second point, that any efforts to suboptimize design costs by requiring competitive bidding for professional services are likely to produce much higher project costs in the long run. The tight control of budget through a high-performance team made the sustainable building (even net zero building)'s construction cost comparable to that of conventional building, in this dissertation, actually is lower that the conventional building.

7.5.2 Collaboration and communication is predetermined by the procurement method

Team collaboration method and quality in all studied projects was largely defined by the procurement method and project delivery method. Benefit of DB is not to reduce the coordination, rather, it is to create an integrated infrastructure. Compared to a typical DBB project, a DB process requires project team to develop robust design including structural concepts, budget and schedule in addition to architectural concept, to compete for the job during the procurement phase. By the time the GSA making selection, the selected team already had more in design development than a traditional DBB project. By having more robust design information, the risk typically bear by the project team in the construction phase can be mitigated during the design phase. The cost overrun burden previously carried by contractor can be shared by the entire team. Such risk mitigation and risk sharing infrastructure derived from the procurement and project delivery method used in DB project typically elevate the heavy dependency of communication and collaboration among team members in the traditional DBB project. This can explain why communication and collaboration showed less influence from the data analysis in Chapter 6. This also can partially explain why some very complicate project with high energy efficiency goal (net zero energy) was able to build within budget, such as Case 1.

One very important finding from this study is the quality of communication is more important than the frequency and quantity of the communication. The communication frequency and volume can be less in DB than that in DBB due to the limited communication channels, that can be interpreted as less communication. In a DBB project, there are many communication channels between design firms, and firms to client, overcommunication can cause the miscommunication and information overflow. On the other hand, with controlled communication channels and well-organized communication method, in DB project like case 1 and CMc project like case 2, the effective communication and collaboration can help team to overcome technical and budget challenges.

In addition, the communication and collaboration are also determined by the team skill and experience. The more experienced team with high skill would know how and when to communication, and they would also know what kind of collaboration are needed for the projects. Overall, a more experienced and skilled team can have more effective communication and better collaboration.

7.5.3 Technical difficulties and complexity are not always related to sustainability

The three case projects show the technical difficulty are not necessarily derived or related solely to the high sustainability and high energy efficiency goals. In case one, WAFB project, the challenge was mainly related to the parallel requirement of historical preservation and net zero energy goal; the technical complexity was dictated by two factors: the building remained occupied during construction, and the design required many reviews from the State Historic Preservation Office (SHPO) because of the building's listing on the National Register of Historic Places. In case two, EWWG building, the technical complexity is mainly caused by the sophisticated layered façade (recladding the entire existing building) and the implementation of a radiant cooling system, that is not common in the United States. In case three, HMM building, the target sustainability level was not significant, the technical complexity was induced by the conflicting needs of modernization and historical preservation.

7.5 Chapter Summary

Chapter seven presents the case studies results to better understand how project team characteristics' influencing the construction cost. In summary, the selected projects represent high, low and mean construction cost of projects included in this research. They are good examples demonstrating the success of achieving sustainability goal while controlling construction cost within the budget. Yet they are not so unique that their successes cannot be repeated. The researcher acknowledge that some aspects of these project teams are difficult to replicate for others (either due to the ARRA, or unique condition induced by historical preservation requirement), others can be repeated for future projects, such as select skilled and experience team and investment in front-end design. The hope is that those case studies provide the impetus and support for important discussions that will elevate all future sustainable projects and project teams.

Chapter 8 Discussion, Conclusion and Future Direction

8.1 Review of Research Objectives

This research project uses empirical data to understand: (1) the sustainable building construction cost (SBCC) in relation to level of sustainability, (2) the influence of soft cost related to the design team to the SBCC, (3) the influence of human factors (indicated by project design team's characteristics) to SBCC, (4) the underlying reason of the influential human factors. In order to gain such understanding, the specific objectives in the project are:

Objective 1: the global status of sustainable building construction cost

Objective 2: investigate the soft cost's impact on total construction cost

Objective 3: evaluate the pattern of correlation/covariance among project characters, human factors, and level of sustainability to SBCC

The three research objectives are addressed in four research phase as illustrated in Figure 8.1. This research project is composed of four phases: Phase One is meta-analysis, Phase Two is creating SBCC database, Phase three is data analysis, Phase four is case studies and conclusion.

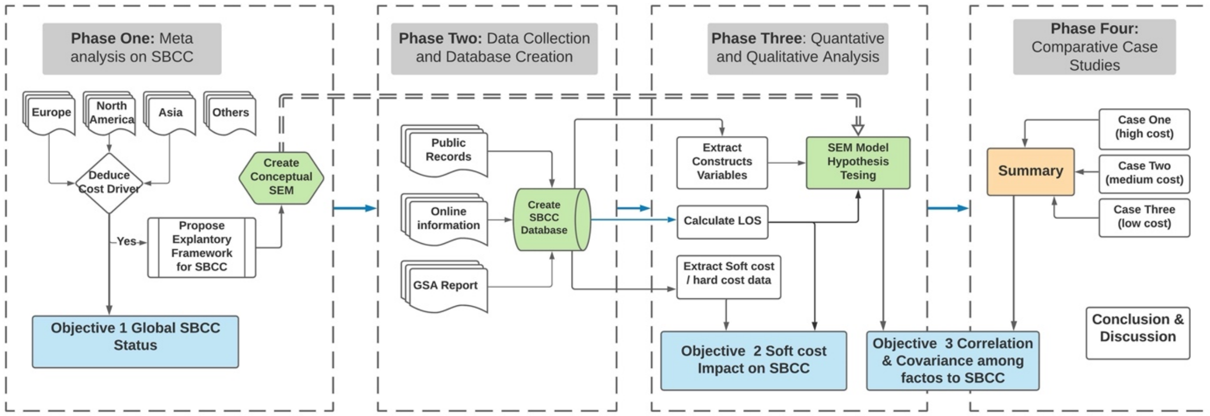


Figure 8.1 Research phases and workflow

Altogether, 10 hypothesis listed in Table 6.1were tested using regression model and structural equation model to study the causal influence of human factors to the total construction cost.

Table 8.1 Tested Hypothesis

H #	Description
H1a	There is no correlation between the construction cost and the level of sustainability
H1b	The primary components contributing to the higher cost of sustainable buildings are derived from the hard costs.
H2a	The human factor has negative effect on the final sustainable building construct ion cost.
H2b	The projects characteristic has insignificant effect on the final building construct ion cost.
H2c	The procurement method has positive relation to human factor.
H2d	The skill level of project team in design has positive relation to human factor.
H2e	The experience level of the project team in design has positive relation to human factor.
H2f	The communication within the project team in design has positive relation to human factor.
H2g	The collaboration within the project team in design has positive relation to human factor.
H2h	The motivation to innovate of the project team in design has positive relation to human factor.

8.2 Summary of Dissertation

In broad terms this research provides empirical evidence that bolster human factors' impact on controlling construction cost of sustainable building. This dissertation first provides a systematic meta-analysis on the SBCC at global scale. Then this dissertation provides the first-kind of SBCC database using the actual construction cost data provided by GSA, the database including the project across the United Sates and cover project certified at different LEED levels. The project design team's characteristics are found and added to SBCC database. Using SBCC database, the researcher then investigates the impact of human factors (project design team's characteristics) on total construction cost. After confirming the important impact of design team characteristics on total construction cost, the mechanisms behind those factors are further examined though comparative case studies.

In Chapter 1, the general background on the subject and motivation of this research project is provided. The theoretic background of research and overarching research questions are laid out. The research objectives and significances are identified. Chapter 2 provides a comprehensive literature review on SBCC as well as the speculative causal factors for higher SBCC. Chapter 3 explains the research design, methodology and strategies for this dissertation. Four research phases are outlined in Chapter 3. Following the Chapter 3, Chapter 4 explain the *Phase One* research findings. The summary of current green building construction cost status is drawn on the meta-analysis findings from Phase one. *Phase Two* research, the SBCC database resource and creation procedures are then explained in Chapter 5. The data of cost factors (outlined in Chapter 1) are extracted for the next step data analysis. Chapter 6 focuses on Phase Three research findings. First, the regression model rejects the hypothesis that soft cost is not the influential factors to the total construction cost. In addition, regression analysis results of the correlation between level of sustainability to the total construction cost is inconclusive. From the SEC analysis, multiple hypothesis are tested. The results of hypothesis testing first demonstrates that project characteristics (e.g. technical complexity) has insignificant impact on the final construction cost, rather, the human factors have significant impact on final construction cost. Within the human factors, project team skill and experience are dominating factors to the final human factor score, while collaboration and motivation to innovate has insignificant influence. The potential interpretation are offered to explain the misalignment between findings from this study to the common perception, such as the importance of project team collaboration and innovation.

Chapter 7 is comparative case studies findings that provide deeper understanding mechanism behind those influential cost factors, and the explanation why the common perception of sustainable building being expensive is not supported by the data. The results of three case studies also provide the evidence that through early design control, the construction cost of sustainable building can be comparable to conventional building, even lower than conventional buildings.

8.3 Discussion of Findings

The findings from this dissertation differ from previous studies in three aspects. *First,* conclusion can be deduced from the regression analysis: the soft cost that associated with design fee bear an important impact on the total project construction cost regardless its small portion to the total construction cost (less than 10%). Moreover, its influence is almost the same as hard cost combined (hard cost includes cost of materials, equipment, and labor). Project team' influence during the early design stage on total construction cost has not been given enough attention in comparison to the focus on project team's performance during the construction phase. More specifically, the design team's qualification has not been regarded widely as a key factor driving the cost of sustainable building due to its small portion of total construction cost. The finding from this dissertation study proved the importance of design team characteristics (human factor influence). Such findings can be explained by the concept of effort curve (refer to Chapter 1): the most important decisions related to cost and cost risk are decided in the early design phase. Unlike conventional anecdotal evidence or intuitive understand, this dissertation provides solid evidence using empirical construction cost data.

Secondly, different from the common perception of collaboration and innovation being critical for project schedule and cost control, this study found no influence of collaboration and innovation. Project team skill and experience are dominating factors.

Thirdly, this study also found project technical complexity and project location are not influential to the total construction cost. Such different findings can be explained by the in-depth case study. Case study of three GSA projects with detailed cost breakdown, project description, project team interview and summary of lessons learned demonstrate that the so called "technical complexity" and "technical difficulty" are mainly induced by two resources: project teams' unfamiliarity to certain technology (not necessarily new), and the restriction and constraints related to other project requirements, such as historical preservation. Those types of technical complexity and/or difficulty can be very well mediated by bringing experienced and skilled team members who are familiar with the systems and regulations.

8.4 Contribution of Research

8.4.1 Contribution to research on sustainable building construction cost

This study on SBCC as an independent topic can cultivate in-depth knowledge of sustainable building practices, consequently creating a research framework/method to examine construction cost-related sustainability barriers. In addition, the investigation focusing on human factors through the design phase can provide unique insights into the effective and alternative strategies to control the construction cost. To this end, the contribution of this dissertation research can be explained in two levels. ***First***, at empirical evidence level, the creation of SBCC database provides an order-of-magnitude increase in the quality and quantity of empirical data. To researcher's knowledge, there is no such an open accessible construction cost data of sustainable building available to practitioners and researchers in the United States. ***Second***, at in-depth evidence level, the case studies provide the detailed information (description and quotes) from project team (include designers, contractors, and GSA managers) that explain why and how the human factors had direct or indirect impact on total construction cost. ***Third***, and methodology level, the researcher made attempt to create SEM using the combination of quantitative and qualitative data, such method can be employed to study other construction cost related research problems.

8.4.2 Contribution to practice

Global concerns over climate change and sustainability have spurred the need for green buildings in the construction industry (Qian & Foong, 2013). Even though the life cycle cost benefits and environmental benefits of green buildings have been extensively studied and documented for decades (Russ et al., 2018), the adoption and promotion of building green still faces tremendous obstacles. Currently, the incremental initial construction costs are oftentimes solely borne by developers, while environmental benefits and other benefits are split among building owners, operators, and occupants. The common perception of sustainable building being expensive hinder the developer's willingness to pursue sustainability. The findings of this dissertation provide evidence that the LEED GSA buildings construction cost is comparable to non-LEED commercial office building. The findings are particularly important and informative for the private developers who are working on existing building retrofit projects with high sustainability goal. As identified in Chapter 6 and 7, the project team's skill and experience played important role in controlling the construction cost and mitigating the risk of cost overall in GSA buildings, such findings can provide insights to the private sector.

It should be noted that although findings indicate that there is not significant influence of communication and collaboration to the construction cost, the findings were derived from a specific set of project data (GSA LEED buildings). The importance of communication and collaboration are reflected in the procurement method. Currently, such finding cannot be generalized to all sustainable buildings, project construct cost data other than GSA building are needed to either validate or amend the findings.

8.5 Impact of Research

The specific impacts of the research proposed in this dissertation can be described at three levels: practice, policies, and industry. ***First*,** at the project and practice level, the empirical data analysis and case studies of the SBCC can better prepare architects and engineers to design cost-effective SBs. ***Second*,** at the policy level, a better understanding of the drivers and factors of the SBCC can help policy makers to create policies, regulations, and incentives that can assist the promotion and adoption of sustainable practices in the building and construction industry. ***Third***, at the industry level, identifying the high-cost items of sustainable building can provide direction for the building and construction industry to find solutions to lower the cost. In addition, the research method for this research project can be used to study economic benefits in other sections of sustainable urban infrastructure.

The broad impact of this research is to advance an understanding and knowledge about the SBCC cost as a fundamental means of promoting building green. In general, this research addresses one of the Grand Challenges for Engineers identified by the National Academy of Engineering: restoring and improving urban infrastructure. The findings and methods resulting from this research project can empower architects, engineers, and developers with the knowledge to promote affordable sustainable building. Knowledge created through this research will provide empirical evidence and explanation why the sustainable building can be affordable to all people, hence to help policy makers to make informative decisions.

8.6 Limitation of Research

The objective of this research is to explore the impact and influence of human factors on SBCC. There are two primary limitations in this research. The first limitation is directly related to the data source of this research. Majority data samples were collected from one institution (one client), that do not reflect wide range or market demand and project types. In addition, becoming the GSA contractor (design and construction) require complicate qualifying process, therefore, the qualified companies are limited compared to firms who work on private sector projects. Consequently, the results of the human factor analysis can not be generalized to describe all sustainable projects. The second limitation is related to the measure index. For example, in this study, the supply chain maturity is represented by the material availability, such single index can create certain bias toward the overemphasis the material selection in sustainable projects.

As for the selected project team characteristics, collaboration and communication factors could be lumped into the design team skill and experience for two reasons: (a) it is difficult to measure, and (b) good design teams know what level of collaboration and communication needed. Therefore the covariance of the project team characteristics can be too strong for double counting the results.

8.7 Direction of Future Research

The work presented in this dissertation presents three clear directions/ paths for future research. First, the inconclusive results from the hypothesis testing regarding the correlation between construction cost and level of sustainability ask for further analysis using more real project construction cost. The current common perception about high construction cost are largely derived from the survey results, and even from the meta-analysis conducted by the researcher, among the included 31 studies, only 21% of studies were able to obtain the actual construction cost data and documents from the project team, and 25% of studies relied on survey or questionnaire responses from the project team members (architect, interior designers, engineers) and clients/developers. The lack of studies based on actual building construction cost can potentially play important indirect role in populating the perception about green building cost more. Even though the findings from this dissertation can not be generalized to all sustainable building, however, the method developed in research can be applied to additional data samples, particularly the data from private sectors. It is interesting to pointing out such findings is aligning with another independent studies examine 37 DGNB certified projects. DGNB stands for (in German) the German Sustainable Building Council, that is non-profit organization based in Stuttgart founded in 2007. The 37 buildings included 8 multi-story residential buildings, 21 office buildings and 8 terraces' houses. All projects are located in Denmark, built between 2012 and 2019 (BUUS Consult, 2020). The total construction costs of those projects range from €800/m^2 (\$86/ft^2) to €3200/m^2 (\$345/ft^2), which are comparable to the GSA projects included in this dissertation study as well. DGNB study results show more sustainable buildings are not necessarily more expensive. Neither higher DGNB award levels nor lower environment impacts levels are necessarily associated with higher construction cost. This study is one of very few studies showed the no correlation between construction cost to the level of sustainability. The researcher has already reached out for data sharing. The plan is to combine the dataset and make joint effort to create robust database that enable researchers to conduct more empirical research to combat the misperception of causal relation between sustainability and higher construction cost.

Second, the proved impact of human factors, particularly the project team skill and experience should be further validated using project data from the private sectors. If the future findings hold the same results, strategies can be formed around control the construction cost and reduce the risk of cost overrun through early project planning. This dissertation focusses on six human factors additional human factors can be included to create a more comprehensive understanding the mechanism how human factors help to mitigate the cost risk, the best practice identified then can be applied as standard procedure in all future projects. As for the project skill and experience, focused in-person review can be used to collect first-hand information from the successful projects included in the SBCC database, and curated questions can help to draw out the clear understanding of what types of skill and experience are most critical in relation to control the construction cost in the context of pursuing sustainability.

Third, in this dissertation, supply chain maturity is indicated by the material availability, the use of single measure can oversimplify the important issue. More thorough investigation is required to elaborate on the impact of supply chain on the construction cost of sustainable buildings. In this regard, it would be interesting to analyze how the construction cost of LEED buildings at same level differ in different geographic location in the United States. Moreover, the summary statistics in Chapter 5 provide evidence of construction cost difference in primary metropolitan areas. Further empirical analysis with breakdown construction cost data (building system and assemblies) can provide more evidence on make a stronger case of supply chain's importance.

Appendices

Appendix A. GSA Letter (FOIA Request)

Office of General Counsel
FOIA Requester Service Center

May 12, 2021

Professor. Ming Hu
University of Maryland
3835 Campus Drive
College Park, MD 20742-0001

Dear Dr. Hu:

This letter is in response to your U.S. General Services Administration (GSA) Freedom of Information Act (FOIA) request number (GSA-2021-000797), submitted on March 15, 2021, in which you requested the following:

1) "Construction cost information of all LEED certified government buildings."

You further clarified your FOIA request on March 25th, March 29th and then again on April 5th agreeing that GSA will provide the following:

> "[a]n approximate 'cost premium' percentage that GSA uses to estimate incremental additional cost of legislative requirements that apply to our projects, including LEED"
>
> and
>
> "[a]n individual construction/ major modernization cost number for each specific GSA-owned LEED- certified building, reflecting available FY2003 to present financial data. For each building, the construction/ modernization investments will be borken [sic] out by five relevant funding categories: capital construction, capital modernization, and Recovery Act.
>
> The report will also provide a building-specific total, and a total for all 175 GSA owned LEED certified buildings that were on record as of 3/31/2021."

Enclosed please find the document responsive to your request.

This completes our action on this FOIA request. Should you have any questions, please contact Walter Tersch at walter.tersch@gsa.gov or (202) 501-0477. You may also contact the GSA FOIA Public Liaison, Duane Smith at (202) 694-2934 or by email at duane.smith@gsa.gov for any additional assistance and to discuss any aspect of your FOIA request.

U.S General Services Administration
1800 F. Street, NW
Washington, DC 20405
Toll Free: (855)-675-3642
Fax: (202) 501-2727

Appendix B. Appendix to Chapter 4 and 5

Case #	Normalized Cost ($/sf)	Certification Level (1-5)	LEED Score	Normalized Score			
				Certified	Silver	Gold	Platinum
1	26	2	51		0.85		
2*	450	3	63			0.57	
5	716	3	45			0.65	
6	1066	3	64			0.58	
7*	350	3	60			0.55	
8 *	69	4	80				0.73
9	311	4	82				0.75
11*	28	1	45	0.41			
12	623	2	27		0.47		
13	242	2	50		0.45		
14	706	3	60			0.55	
15	558	4	80				0.73
16	153	4	80				0.73
17	215	4	80				0.73
18*	1248	4	83				0.75
19*	276	2	60		0.55		
19b	117	2	54		0.49		
20*	33	4	81				0.74
21*	313	3	66			0.6	
22	206	2	52		0.47		
24	20	2	54		0.49		
25	9	1	47	0.43			
27	2	1	41	0.37			
28	34	2	53		0.48		
29	1	1	40	0.36			
30	2	1	44	0.40			
31	93	1	48	0.44			
32	22	2	56		0.51		
33*	183	3	42			0.60	
34*	256	3	46			0.66	
36*	928	3	60			0.54	
37*	312	2	42		0.60		
38*	13	2	46		0.66		

41	42	2	60		0.54		
42	28	1	41	0.37			
43	111	1	45	0.41			
44	10	1	42	0.38			
45	2	1	40	0.36			
46	380	1	48	0.44			
47	139	1	42	0.38			
48	93	1	45	0.41			
49	216	1	47	0.43			
50	16	1	47	0.43			
50b	212	3	62			0.563	
51*	253	3	65			0.59	
52	370	3	60			0.54	
53	460	3	64			0.58	
54	175	3	62			0.56	
55	99	1	42	0.38			
56	433	3	60			0.545	
58	496	1	41	0.37			
62	172	3	67			0.60	
63	150	3	65			0.59	
65*	165	3	32			0.56	
66	24	2	53		0.48		
67	10	3	38			0.66	
68*	191	3	75			0.68	
70	7	2	50		0.45		
71	36	1	48	0.44			
74	46	1	42	0.38			
75	12	1	43	0.39			
80	388	3	39			0.56	
81	19	1	44	0.40			
82	304	4	80				0.72
86	165	1	45	0.41			
87	0	1	44	0.40			
88	64	1	40	0.36			
89*	264	2	52		0.47		
92	499	3	41			0.59	
94	318	2	45				

96	176	3	60			0.54	
97	525	3	60			0.54	
98	220	3	60			0.54	
99	801	1	40	0.36			
101	133	3	62			0.56	
102b	1	1	42	0.38			
103	236	2	42		0.38		
105	19	1	40	0.36			
106	2	1	43	0.39			
107	475	2	64		0.58		
113*	171	1	47	0.43			
114	105	2	53		0.48		
115	14	1	40	0.36			
116	20	4	80				0.72
117*	251	4	84				0.76
118	3	1	46	0.42			
119	194	2	58		0.52		
120	3	2	46		0.41		
121	60	1	44	0.40			
122	127	1	44	0.40			
123	97	2	56		0.51		
125	0	1	43	0.39			
127	8	2	56		0.51		
128	1	1	44	0.40			
130	232	4	88				0.8
132*	214	4	85				0.77
136	300	1	40	0.36			
138*	42	1	46	0.42			
139	27	1	46	0.42			
140	1	2	51		0.46		
141	164	3	50			0.45	
142	240	2	33		0.47		
143	11	1	47	0.43			
144	10	3	60			0.54	
144b	391	2	51		0.46		
145*	44	1	45	0.41			
146*	136	2	57		0.51		
147	82	2	65		0.59		
148	198	1	47	0.43			
149	1173	3	47			0.42	

153*	351	3	61	0.61
154	120	1	41	0.37
155	15	1	33	0.30

Certification Level

0.5	No
1	Certified
2	Silver
3	Gold
4	Platinum
5	Net zero energy

Appendix C. Appendix to Chapter 4 and 5 (Sample of cost breakdown data and LEED score card)

C1: Cost breakdown of LEED Philip Burton courthouse

PHILLIP BURTON,FB CT			
	Items	**Cost ($)**	**Percentage**
Hard Cost	Exterior Construction (façade)	$7,529,000	
	Interior Construction	$1,023,000	
	Electrical System	$928,000	
	Fire Protection System	$300,000	
	HAVC System	$980,000	
	Plumbing System	$2,955,000	
	Repair/Replace Roof	$2,385,000	
	Demolition /Sitework	$8,899,000	
Subtotal		**$24,999,000**	**92%**
Soft cost	Design	$2,000,000	
	Management	$100,000	
	Inspection	$100,000	
Subtotal		**$2,200,000**	**8%**
Total		**$27,199,000**	

1000023647, SAN FRANCISCO, California

Phillip Burton Fed Bldg and US C H

LEED O+M: Existing Buildings (v2009)

CERTIFIED, AWARDED JAN 2013

SUSTAINABLE SITES		AWARDED: 4 / 26
SSc1	LEED certified design and construction	0 / 4
SSc2	Building exterior and hardscape Mgmt plan	1 / 1
SSc3	Integrated pest Mgmt, erosion control, and landscape management ...	1 / 1
SSc4	Alternative commuting transportation	0 / 15
SSc5	Site development - protect or restore open habitat	1 / 1
SSc6	Stormwater quantity control	0 / 1
SSc7.1	Heat island effect - nonroof	1 / 1
SSc7.2	Heat island effect - roof	0 / 1
SSc8	Light pollution reduction	0 / 1

WATER EFFICIENCY		AWARDED: 6 / 14
WEp1	Minimum indoor plumbing fixture and fitting efficiency	REQUIRED
WEc1	Water performance measurement	0 / 2
WEc2	Additional indoor plumbing fixture and fitting efficiency	5 / 5
WEc3	Water efficient landscaping	0 / 5
WEc4	Cooling tower water Mgmt	1 / 2

ENERGY & ATMOSPHERE		AWARDED: 21 / 35
EAp1	Energy efficiency best Mgmt practices - planning, documentation ...	REQUIRED
EAp2	Minimum energy efficiency performance	REQUIRED
EAp3	Fundamental refrigerant Mgmt	REQUIRED
EAc1	Optimize energy efficiency performance	16 / 18
EAc2.1	Existing building commissioning - investigation and analysis	0 / 2
EAc2.2	Existing building commissioning - implementation	0 / 2
EAc2.3	Existing building commissioning - ongoing commissioning	0 / 2
EAc3.1	Performance measurement - building automation system	0 / 1
EAc3.2	Performance measurement - system-level metering	0 / 2
EAc4	On-site and off-site renewable energy	3 / 6
EAc5	Enhanced refrigerant Mgmt	1 / 1
EAc6	Emissions reduction reporting	1 / 1

MATERIAL & RESOURCES		AWARDED: 2 / 10
MRp1	Sustainable purchasing policy	REQUIRED
MRp2	Solid waste Mgmt policy	REQUIRED
MRc1	Sustainable purchasing - ongoing consumables	0 / 1
MRc2.1	Sustainable purchasing - electric-powered equipment	0 / 1
MRc2.2	Sustainable purchasing - furniture	0 / 1
MRc3	Sustainable purchasing - facility alterations and additions	0 / 1
MRc4	Sustainable purchasing - reduced mercury in lamps	1 / 1
MRc5	Sustainable purchasing - food	0 / 1
MRc6	Solid waste Mgmt - waste stream audit	1 / 1

MATERIAL & RESOURCES		CONTINUED
MRc7	Solid waste Mgmt - ongoing consumables	0 / 1
MRc8	Solid waste Mgmt - durable goods	0 / 1
MRc9	Solid waste Mgmt - facility alterations and additions	0 / 1

INDOOR ENVIRONMENTAL QUALITY		AWARDED: 5 / 15
EQp1	Minimum IAQ performance	REQUIRED
EQp2	Environmental Tobacco Smoke (ETS) control	REQUIRED
EQp3	Green cleaning policy	REQUIRED
EQc1.1	IAQ best Mgmt practices - IAQ mana...	0 / 1
EQc1.2	IAQ best Mgmt practices - outdoor air delivery mo...	0 / 1
EQc1.3	IAQ best Mgmt practices - increased ventilation	0 / 1
EQc1.4	IAQ best Mgmt practices - reduce particulates in ...	0 / 1
EQc1.5	IAQ best Mgmt practices - IAQ mana...	0 / 1
EQc2.1	Occupant comfort - occupant survey	0 / 1
EQc2.2	Controllability of systems - lighting	0 / 1
EQc2.3	Occupant comfort - thermal comfort monitoring	0 / 1
EQc2.4	Daylight and views	0 / 1
EQc3.1	Green cleaning - high performance green cleaning program	1 / 1
EQc3.2	Green cleaning - custodial effectiveness assessment	1 / 1
EQc3.3	Green cleaning - purchase of sustainable cleaning products and materia...	1 / 1
EQc3.4	Green cleaning - sustainable cleaning equipment	0 / 1
EQc3.5	Green cleaning - indoor chemical and pollutant source control	1 / 1
EQc3.6	Green cleaning - indoor integrated pest Mgmt	1 / 1

INNOVATION		AWARDED: 5 / 6
IOc1	Innovation in operations	1 / 1
IOc2	LEED Accredited Professional	1 / 1
IOc3	Documenting sustainable building cost impacts	1 / 1

REGIONAL PRIORITY CREDITS		AWARDED: 2 / 4
EAc1	Optimize energy efficiency performance	1 / 1
EAc4	On-site and off-site renewable energy	0 / 1
WEc2	Additional indoor plumbing fixture and fitting efficiency	1 / 1

INTEGRATIVE PROCESS CREDITS		AWARDED: 0 / 2
IPpc89	Social equity within the community	REQUIRED
IPpc90	Social equity within the operations and maintenance staff	REQUIRED

TOTAL 45 / 110

40-49 Points	50-59 Points	60-79 Points	80+ Points
CERTIFIED	SILVER	GOLD	PLATINUM

C2 LEED Score card of LEED Philip Burton courthouse

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