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PILOTING EVALUATION METRICS FOR HIGH PERFORMANCE GREEN BUILDING PROJECT DELIVERY

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by

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ABSTRACT

High-performance green (HPG) buildings are becoming more widely adopted due to their potential to reduce energy costs, and to improve the health and productivity of occupants; creating an expectation of $10-20 billion value of green building construction starts by 2010, reported by Mc-Graw Hill. The emphasis on energy and indoor air quality aspects of high-performance green buildings leads to a need for superior planning, design and construction processes to achieve high-performance green goals within realistic financial and time constraints. The current literature offers product based high-performance metrics as a part of existing building assessment systems (e.g. LEED™ and Green Globes™) as well as metrics to study actual building performance, but lacks descriptive project delivery evaluation metrics.

This gap in the literature inhibits project teams to fulfill the desired project goals and results with missed opportunities in the delivery process and shortcomings in the project performance outcomes. The limited green building population and the lack of knowledge about important project delivery evaluation metrics and methods to collect data in this field present the first challenge in HPG building project delivery research. Acknowledging these limitations, the purpose of this research is to advance the knowledge needed to deliver HPG buildings by piloting evaluation metrics for HPG building delivery.

The research is exploratory in nature that aims to provide a foundation for future research by defining meaningful evaluation metrics, methods and tools to collect and analyze HPG building project delivery data. A mixed method is utilized to achieve these aims that start with a quantitative analysis examining a pool of HPG project delivery data collectively and than continues with a qualitative analysis to support the findings of quantitative analysis and draw additional lessons from case studies. The results lay a foundation for rigorous and high yield HPG building project delivery research and form a guide for the green building community to better deliver high-performance green building projects.

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Chapter 1

Introduction

High-performance green (HPG) buildings are "green" or "sustainable" buildings which exhibit maximum energy efficiency of envelope, mechanical and lighting systems coupled with improved indoor environmental quality to enhance occupants' well being. HPG buildings are enjoying increasingly wider adoption due to their potential to reduce energy costs, and to improve the health and productivity of occupants. Greater interest is fueling expansion architectural, engineering, and construction (AEC) industry demand to accommodate the HPG building market. Analysts expect $10-20 billion green building construction starts by 2010 (MCH, 2007).

The emphasis on energy and indoor air quality aspects of high-performance green buildings leads to a need for superior planning, design and construction processes to achieve high-performance green goals within realistic financial and time constraints. These projects often require integrated design approaches to perform complex design analyses, energy modeling, and system optimizations (Riley et al., 2004). Many green building practices fail to achieve their set goals due project teams' lack of understanding of "green" strategies, and introduction of "green ideas" to projects as afterthoughts.

Although widely accepted in the green building community, owners' commitment, integrated design, and inclusive project teams are essential for high-performance green building project delivery; little discussion considers the effects of project delivery processes on project performance outcomes. Overall, the elements of HPG buildings are well recognized in the construction community, but the best ways to deliver these buildings are yet to be explored.

The data needed to define relationships between project delivery attributes and project performance outcomes is challenging to collect and capture. The low response rate to Department of Energy's high-performance building project database survey (DOE, 2006), in particular the limited knowledge garnered regarding project delivery due to poorly designed survey questions, and a recent research conducted by Green Building Alliance (GBA, 2006) on the meaningful and collectable building actual performance metrics are clear indications of the difficulty involved with capturing relevant data. Defining evaluation metrics for HPG building project delivery, forming the right questions to capture these metrics, selecting the most important variables for attention in the data collection process, and the methods/tools to collect this data are essential research subjects necessary for carrying this research to a higher level of relevance and usefulness. To do so allows accumulation and study of the affects of project delivery attributes on performance outcomes in HPG buildings, and allows for continuous refinement of the project delivery processes.

The purpose of this research is to contribute to the knowledge needed to deliver HPG buildings by piloting evaluation metrics for HPG building delivery. This research is a pioneering effort, previously avoided due to: (1) The extensive number of variables with a potential impact on HPG project performance; (2) The lack of rigorous research exploring green building project delivery in the literature; (3) The limited project population size due to the green building market's infancy; (4) The challenges field researchers face for collecting meaningful project delivery data, and (5) The immaturity of the learning curve for the evolution of green design and building practices. Therefore, for any given project data, collected from the industry is subject to changes and evolution as teams' levels of experience develop.

For these reasons, this research is a pilot study of the HPG building market and is exploratory in nature with the aim of providing a foundation for future research by defining meaningful evaluation metrics, methods and tools for collecting HPG building project delivery data. The research employs mixed methods: a quantitative analysis to examine a collective pool of HPG project delivery data, and a qualitative analysis to triangulate the findings of quantitative analysis and draw additional conclusions from case studies.

1.1 Background

"High-performance green building" is a concept developed in recent years parallel to environmental and market needs. Investigation of methods of project delivery determines the contribution and limitations of key processes in terms of project success. However, project delivery processes for HPG buildings have yet to become the subject of rigorous research efforts.

1.1.1 High-performance Green Building Market

In recent years high-performance green buildings have received major attention for several different reasons, the most important of which are the business incentives that these buildings offer to building owners and the public's general mindset-shift toward environmental concerns. One important and expanding motivation for owners to build HPG buildings is the increase in energy costs and the uncertainty surrounding future energy costs. As the primary consumers of energy, buildings collectively consume about 39% of all energy and 71% of all electricity in the United States (USGBC, 2007). As energy costs have risen, owners have increasingly begun make investments in energy efficiency which favor of low life-cycle costs. Another motivation for owners to build HPG buildings is that the intangible benefits of indoor environmental quality have been proven to lead to major cost benefits. People spend approximately 90% of their time indoors in the U.S. (Morton, 2002). Several studies documented that daylighting, increased control over ventilation and lighting, and healthy indoor environmental conditions may help to improve learning, increase productivity, and reduce sick time (HMG, 1999; Heerwagen, 2000; Loftness et al., 2002; Fisk, 2000). Research findings on IEQ showed that operating and personnel costs (totaling up to 99% of the business expenses related to building and personnel costs) over the life-cycle of a building considerably exceed the design and construction costs (DOE, 2003). Obviously the motivation exists for owners to build HPG buildings.

Global and national sustainable agendas also brought attention on HPG buildings due to environmental concerns. Buildings, in the U.S., produce 38% of primary greenhouse gas emissions associated with global climate change (USGBC, 2007) which emphasizes the importance of the construction industry's role in the national sustainability agenda. The expected value of green building construction starts is between $10-20 billion through 2010 (MCH, 2007). This growth represents a large share of the U.S. construction industry where the total construction in 2006 was $ 1.2 trillion (USCB, 2006).

The growing demand for HPG buildings generated the need to develop criteria for HPG building design and construction, as well as to evaluate how "green" and "high performing" these buildings are. The existing criteria in the literature can be classified into two major categories:

1) Building assessment system criteria focusing on the end product of the project delivery process, developed by, e.g., the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED^{TM}) and Green Globes^{TM}, distributed by Green Building Initiative (GBI) in the U.S., and

2) Actual building performance criteria focusing on the post-occupancy phase of the buildings developed by Pacific North National Laboratory (Fowler et al., 2005), Environmental Protection Agency's Energy Star Rating System (EPA, 2006), US Department of Energy (DOE, 2006) and recently Green Building Alliance (GBA, 2006).

Building assessment systems certify buildings depending on the sum of points achieved in each of the evaluations' subsections; therefore the sum of points achieved in each system is not descriptive in terms of the of products' high-performance levels. Actual building performance data on the other hand, is difficult to obtain and is not all types of owners' immediate consideration. Instant success measures as a result of the project delivery processes are more attractive for owners. None of these systems employ project delivery process metrics in their evaluation criteria other than some building assessment systems with very limited criteria in their innovative design subsections.

1.1.2 Project Delivery Research

Project delivery and contracting strategies define how project teams form, their working relationships and levels of involvement during project timelines, and incentives to encourage contribution of to the project. In the early twentieth century, despite exceptions in the private sector, most projects were completed under traditional lump sum contracts. Construction management emerged in the late 1960s, design-build in the 1970s, and by the 1980s, owners sought more efficient ways to complete complex projects (Dorsey, 1997).

The design of project processes is critical to the success or failure of projects (Sanvido and Konchar, 1997). Recent project delivery research sponsored by Construction Industry Institute (CII) developed metrics for project delivery and statistically compared performance outcomes in terms of cost, schedule, and quality according to design-bid-build, design-build, and construction management at-risk project delivery systems (Konchar and Sanvido, 1998). Design-build procurement methods research (El Wardani et al., 2006) defined methods for collecting data of team procurement processes and also empirically examined the relationship between procurement methods and performance outcomes.

1.1.3 High-performance Green Project Delivery

Different from traditional building projects, high-performance projects require additional considerations in their delivery processes to achieve expected performance goals (Riley et al., 2004). Recent research has shown that early involvement of “green” concepts in projects and owner’s commitment to sustainability enables achievement of sustainability goals at lower costs (Lapinski, 2005; Beheiry et al., 2006). Moreover, the integrated design process is essential for these projects which require increased cross-disciplinary expertise (NIBS, 2005). Team experience (GSA, 2004), early involvement of key project participants (Riley and Horman, 2005), and utilization of energy strategy and simulation tools in the early stages of the design process (Horman et al., 2006) are other key components that lead to superior outcomes in high-performance green projects.

Lack of understanding HPG project characteristics can lead to high project costs (Smith, 2003). More importantly, this deficit is likely to overlook design opportunities in high-performance green projects and as a result of defective delivery processes, culminate with poorly performing buildings. Early decisions in the planning and the design process of a building project lead to improved building performance outcomes. Therefore, a thorough understanding of project delivery attributes by project teams is essential for HPG building project success. Recent research at the Pennsylvania State University has shown that the project delivery method affects both the levels of sustainability achieved and the cost effectiveness of these buildings (Lapinski et al., 2006; Magent, 2005). However, limited research has been directed toward the specific impacts of project delivery systems and processes for the success of high-performance green buildings. A need exists for project delivery evaluation metrics for HPG buildings in the construction community to enable better performing projects. However, examining the large number of variables and capturing the qualitative characteristics of the data for this field challenges data collection for these metrics.

1.2 Problem Statement

The current literature offers product based high-performance metrics as a part of existing building assessment systems (e.g., LEED^{TM} and Green Globes^{TM}) as well as metrics to study actual building performance metrics, but lacks descriptive project delivery evaluation metrics. Understanding project delivery evaluation metrics is important for project teams since critical decisions, such as building orientation, envelope systems selection, or daylighting analyses, affecting building performance outcomes are made early in the process. Lack of project delivery evaluation metrics inhibits project teams' fulfillment of the desired project goals and result in missed opportunities in the delivery process and shortcomings in the project performance outcomes. Research needs to consider HPG project delivery attributes and how they relate to project performance outcomes. The limited green building population and the lack of knowledge of important project delivery evaluation metrics and methods to collect data in this field present the first challenge for the research of HPG building project delivery.

1.3 Description of the Research

This research focuses on piloting evaluation metrics for HPG building project delivery. This section explains the research question, goals, and objectives. Research scope, approach, the steps followed to achieve research goals, and outcomes are also discussed.

1.3.1 Research Question

This research builds the first step in HPG building project delivery research by defining and screening the meaningful project delivery evaluation metrics for HPG building project delivery. These metrics comprise a combination of both project delivery attributes and measurable project performance outcomes. With this intention, the research question this study poses is: "What project delivery attributes relate to performance outcomes in HPG building projects?"

1.3.2 Research Goals

The primary goal of this research is to define project delivery evaluation metrics that are a combination of process indicators and performance metrics for HPG building project delivery. *Indicators* refer to measurable project delivery attributes that can influence project performance and which owners and/or project teams can control.

Metrics refers to measurement of project performance outcomes and are affected by project delivery attributes. After collecting the first set of HPG building project delivery evaluation metrics, they were screened to limit the variables to a set of meaningful evaluation metrics for HPG building project delivery and to define additional metrics not captured previously.

The second goal of this research is to develop a tool and the methods to collect HPG building project delivery data. HPG building project delivery evaluation metrics are a combination of measured and latent variables. Although the literature addresses some of these variables, a need remains for a tool that includes questions targeting the HPG building projects. Additionally, the challenge of accessing project specific data for sustainability performance, project outcomes, and project delivery attributes calls for development of feasible methods for collecting HPG building project delivery data.

The final goal of this research is to provide methods to analyze the collected HPG building project delivery data. Due to the fact that this research is a pioneer effort in its field and is exploratory in nature, the study utilizes a mixed method. First, the study empirically investigates the correlations between the process indicators and performance metrics using quantitative methods to limit the defined set of variables to a smaller set that are meaningful in explaining HPG building project delivery. At this stage, the research investigates diverse types of variables such as categorical and continuous variables and explores the quantitative analysis techniques to investigate HPG building project delivery. Second, the study examines, through qualitative methods, the defined variables characteristic of case study comparisons, triangulates the findings of the quantitative results, defines additional indicators/metrics and alternatives for investigating HPG project delivery.

The results establish a foundation for rigorous and high-yield high-performance green building project delivery research and form a guide for the green building community to improve delivery of high-performance green building projects.

1.3.3 Objectives

The research goal is achieved through the following objectives:

1) *Articulate project delivery attributes and evaluation criteria for performance outcomes of HPG building projects:* A literature review aided understanding of the theoretical background in this area and enabled preliminary assessment of project delivery process indicators and performance metrics.

2) *Develop, test and verify a tool for obtaining data on HPG delivery attributes and performance outcomes:* Research of existing literature and building assessment systems as well as interviews with industry professionals provided information of high-performance process indicators, such as owner commitment, integrated design process, contractual requirements, application process components, and high-performance product metrics. A pre-study, prior to the primary investigation verified the survey questions, the format, and the application strategies, allowing the design of the final version of the survey to gather data in defined areas and for project specifics.

3) *Perform data collection on identified building projects:* Using the developed survey, data collected for defined areas arose from completed high-performance green building projects and allowed detailed quantitative and qualitative analyses on relationships between project delivery processes indicators and performance metrics.

4) *Examine the collected data using mixed methods to identify the HPG building project delivery evaluation metrics:* Data analysis began with a quantitative analysis to select the primary set of evaluation metrics for a definitive comprehensive data analysis and continued with qualitative data analysis to support the findings of the quantitative data analysis. The results are acquisition of additional lessons from the collected data pool based on case studies, and defining additional variables and data analysis methods for HPG building project delivery not captured previously.

5) *Refine the results, summarize research contributions, and construct recommendations for future research:* Results of the mixed method analyses assisted refinement of the evaluation metrics for HPG building project delivery. The study also developed a tool and methods to collect data of high-performance project delivery. The

results showed that the mixed methods beginning with quantitative analysis and continuing with qualitative analysis assisted in achieving study goals. The deliverables of this study provide a foundation for future research and guides the construction community to better deliver HPG buildings. The study recommendations offer a new vision for continuous improvement in the HPG building community.

1.3.4 Scope

The scope of the research is limited to examining the delivery processes of projects that start with the owner's decision to construct a building and ends with the facility's commissioning to the building owner from the design and construction teams. Based on the assumption that, high-performance green strategies, practices, and technologies applied at the design and construction phases of projects lead to actual HPG building performance, this research is limited to the delivery process of the project and excludes actual building performance information associated with the post-construction occupancy.

The following project delivery process indicators and project performance metrics are subject of examination within the limits of this research: 1) Process indicators, e.g., level of owner commitment, project delivery system, team procurement method, contract conditions, team characteristics, integrated design process, and construction data as well as the application related procedure; and 2) Performance metrics, e.g., cost, schedule, quality, safety, and high-performance levels.

Data collection focuses on green building projects due to a lack of methods to identify high-performance buildings in the existing literature. The project sample is limited to recognized green office building projects that received either a green certification or/and an award as an indicator of an effort to employ high-performance or green strategies in these projects. The intent to limit the research population to office building projects is an effort to decrease the variability in the data set.

1.3.5 Results and Deliverables

The results and the deliverables of the research that provide a foundation for future research and recommendations to guide future efforts in HPG building project delivery are:

1) Evaluation metrics to define HPG building project delivery that includes project delivery process indicators and performance metrics;
2) A verified data collection tool and methods for feasible collection of meaningful data on HPG building project delivery; and
3) Methods to analyze collected HPG building project delivery data for defining project delivery attributes that lead to better HPG building project performance outcomes.

1.4 Reader's Guide

The conducted literature review appears in Chapter 2. Chapter 3 describes the methodology to realize the stated research goals and objectives, followed by Chapter 4's demonstration of the development of the data collection tool and presentation of the preliminary project delivery evaluation metrics based on the literature review and pre-study of the data collection tool. Chapter 5 presents the data collection procedures, the strategies to increase the data quality, and the characteristics of the study sample. Chapter 6 describes the steps followed for the quantitative analysis of the collected data as well as its results. Chapter 7 includes data collection techniques for the case study stage of the research, the criteria to meet the quality for the case study evidence analysis, and the results of the qualitative analysis. Last, Chapter 8 presents the results, contributions and limitations of the research, and recommendations for future research.

Chapter 2

Literature Review

High-performance green (HPG) building project delivery research includes the vocabulary of sustainable construction and project delivery metrics used to assess building project performance, previous research on project delivery methods and project-team procurement. This research also encompasses existing efforts to catalog and examine outcomes of "sustainable" or "green" projects by others. "Sustainability" and "green" are used interchangeably in the literature and evoke a variety of impressions. A literature review, conducted first, assesses the existing definitions for these concepts. Next, for the purposes of this study, high-performance green buildings are characterized based on business-driven incentives. Subsequently, a review of building assessment methods, including LEED™ and Green Globes™, examines ways to evaluate merits of green building projects based on the building product features, followed by an exploration of existing project delivery studies and characteristics distinctive of HPG project delivery. The studies that offer development of success factors and performance metrics for project delivery and green building database applications are also reviewed. This chapter summarizes the relevant concepts in HPG project delivery, building environmental assessment systems, and research conducted in this area, as well as a review of existing green building databases. The gaps in the HPG project delivery field are identified to provide direction for this research.

2.1 "Sustainability" and "Green" Concepts

Sustainability practices have been applied by Indian tribes in America for thousands of years. However, within the past decade the terms "sustainability" and "green" have gained recognition in the architecture, engineering, and construction (AEC) industry as the world has become more sensitive towards the issues of environment and global climate change. Although the green building movement in the United States (US) was initiated at the beginning of 1990s with establishment of green building initiatives and national committees, today numerous green building research and assessment programs exist, nationwide. Most green building initiatives embrace similar concepts, yet varying definitions for “sustainability” and “green” remain in the literature. Agenda 21 (CIB, 1999) defines sustainability as “the condition or the state that would allow the continued existence of homo sapiens.” The United Nations World Commission on Environment and Development (Brundtland Commission) Report expresses the most commonly accepted definition of sustainable development (WCED, 1987):

> “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2003) defines green design as the one that minimizes the impacts on natural surroundings, materials, resources, and processes present in the nature. ASHRAE’s definition of green design supports human’s right to exist, build, and grow without having any adverse impact on earth’s resources and affecting habitability of the earth for future generations.

Buildings contributing to major resource and energy consumption, global warming, and ecosystem changes all over the world justify the construction industry as an appropriate focus for efforts toward sustainability. Buildings in the US, collectively, consume about 39 % of all energy, 71 % of all electricity, and produce 38 % of primary greenhouse gas emissions associated with global climate change (USGBC, 2007). Therefore, sustainable construction is vital for continuity between the world’s resources and quality life of human beings, as well as the entire earth’s inhabitants. Agenda 21 for developing countries (1999) describes sustainable construction as a holistic process starting with the extraction of raw materials, continuing with the planning, design, and construction of buildings, and ending with their demolition and management of the resultant waste. Sustainable construction however, requires a different way of thinking that the cost, quality, and time focused traditional construction industry lacks (Vanegas et al., 1995). Sustainable design and construction adopts additional criteria which prioritizes minimal resource consumption and environmental procedures to achieve healthy built environment (Kibert, 1994). Vanegas et al. (1995) point to the paradigm shift in the construction industry with its emerging focus on environmental aspects of sustainability. This paradigm shift in the construction industry has social, cultural, and environmental implication in a global context (Agenda 21, 2003). Figure 2-1 below illustrates this new approach in the construction industry as presented by (Vanegas et. al., 1995).

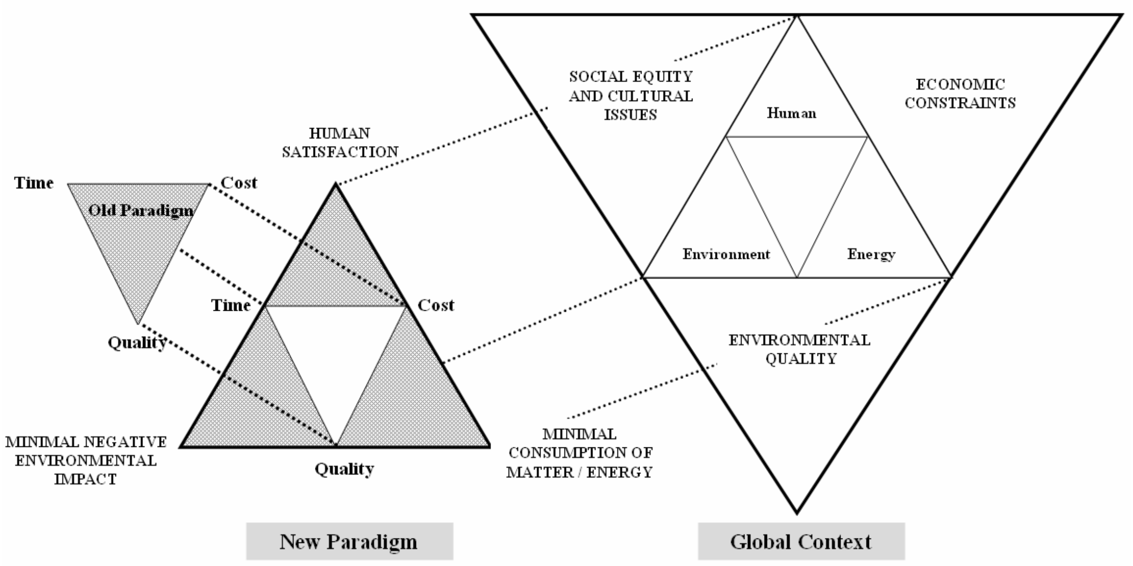


Figure 2-1**:** Paradigm Shift in the Construction Industry (Originally developed by Vanegas et al., 1996, expanded in Agenda 21, 2003).

As a result of this paradigm shift, green buildings have been developed widely in the US. The US Green Building Council (USGBC, 2002) defines green buildings as: “Designed, constructed, and operated to boost environmental, economic, health and productivity performance over that of conventional building.” Green buildings are those that achieve the *minimum* of the following throughout their lifecycles (ASHRAE, 2003):

- Consumption of resources such as land, materials, and water,
- Emissions of green house gases that lead to global warming and climate change,
- Release of harmful liquids and solid waste through demolition processes,

- Adverse impacts on site eco-systems, and
- Deficiencies in indoor environmental quality.

Although green buildings have numerous environmental, social, and economical benefits, certain motivations remain for building green according to different stakeholders. Integrated Delivery System for Sustainable Construction project (IDS, 1998) at Salford University investigated the primary motivations for sustainable construction among different actors in building projects. The study revealed international institutions and national governments' primary objectives in pursuing sustainable construction is reducing global warming. Conversely, for clients and designers, the primary driving force for sustainable construction was, apparently, reducing energy consumption in buildings. Yates (2001) defined the quantifiable benefits of green buildings as increased return on investment; reduced operations and maintenance and costs; marketing developments through "green" image; and increased productivity through employee satisfaction. In summary, both directly saving building costs, and indirect financial benefits from improved performance of occupants of green buildings provide motivation for the organizations to pursue green buildings. Consequently, these explain the market sector growth of high–performance green (HPG) buildings.

2.2 High-performance Green Buildings

While green buildings comprise only a small fraction of all buildings, high-performance green (HPG) buildings are an even smaller fraction of buildings, whose focuses include indoor environmental quality and energy conservation issues. These distinctions warrant further description. Figure 2-2 illustrates how HPG green buildings relate to other types of building definitions.

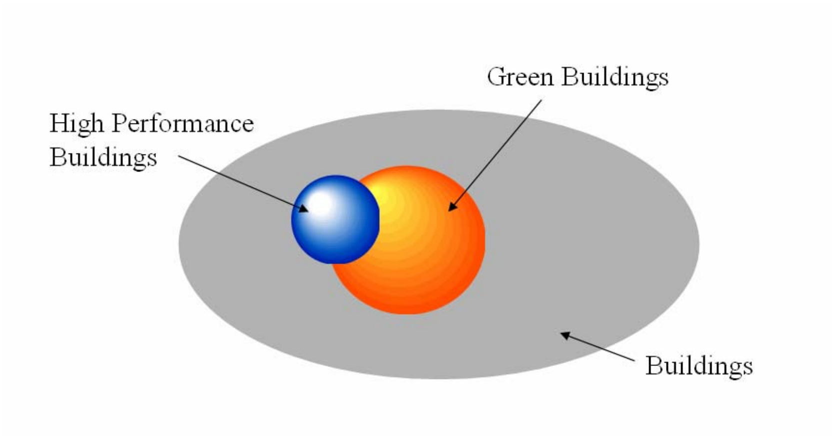


Figure 2-2**:** High-performance green building definition (Horman et al., 2006)

The U.S. Office of Energy Efficiency and Renewable Energy (DOE, 2006) defines a high-performance building as:

> "A building with energy, economic, and environmental performance that is substantially better than standard practice. It's energy efficient, so it saves money and natural resources. It's a healthy place to live and work for its occupants and has relatively low impact on the environment."

Green buildings are, in general, designed to reduce resource consumption through recycling, water and energy conservation strategies, and emissions reductions. However, these strategies do not often lead to significant financial benefits to building and business owners, and in fact, are often perceived as adding cost. High-performance green buildings have the potential to reduce the environmental and economic footprint of buildings by minimizing energy use, reducing resource consumption and waste, and providing healthy and productive environments for occupants (Lapinski et al., 2006). Realizing the return on investment for high-performance facilities occurs through reduced operating costs, occupant satisfaction, reduced absenteeism and increased performance (Kobet et al., 1999).

A report developed for California's Sustainable Building Task Force (Kats et al., 2003) accumulated and analyzed existing data on cost and financial benefits of 33 green buildings in California. The report showed that the tangible financial benefits from green buildings are energy, water and waste savings, and reduced operations and maintenance costs. The results of this report, summarized in Table 2-1, show that substantial cost savings in green buildings accrue through energy related strategies, adopted during the project delivery processes of the green buildings. These strategies include reduction of the operational costs by selecting efficient HVAC and lighting systems and savings in maintenance costs after conducting efficient commissioning processes. Moreover, increased indoor environmental quality yields intangible, and simultaneously, significant financial benefits through improved occupant health and productivity (Kats et al., 2003). The main finding of this study, regarding productivity, is that the greener projects lead to better indoor environmental quality and higher productivity and health value. Specific values of high-performance green buildings' benefits, in terms of net present value (NPV), appear in Table 2-1 which highlights the value of productivity and health as the greatest area of financial benefits for owners. Categories of HPG building attributes and levels of achievement in terms of LEED^{TM} certified, silver, gold, and platinum also appear in Table 2-1 and have further detailed explanation in the following sections.

Table 2-1: Financial Benefits of Green Buildings (Net present value per ft^2) (Kats et al., 2003).

Category	20-year NPV
Energy Value	$5.79
Emissions Value	$1.18
Water Value	$0.51
Waste Value (Construction only) – 1 year	$0.03
Commissioning O&M Value	$8.47
Productivity and Health Value (Certified and Silver)	$36.89
Productivity and Health Value (Gold and Platinum)	$55.33
Less Green Cost Premium	($4.00)
Total 20-year NPV (Certified and Silver)	$48.87
Total 20-year NPV (Gold and Platinum)	$67.31

Energy and indoor environmental quality strategies in green buildings achieve significant cost savings. This business incentive is currently, and will likely continue to be a primary motivator for owners and developers to build high-performance green buildings. The specific benefits of energy conservation and indoor environmental quality strategies are presented in more detail in the following sections.

2.2.1 Energy Conservation

Diminishing energy resources worldwide direct the scientific world to seek alternative energy sources while the rising costs of energy provide incentives for consumers of energy to conserve. Although traditionally driven by first-cost financial constraints, the following facts compel building owners to place a priority on life-cycle costs and energy efficiency of the buildings over initial construction costs: 60% to 85% of a building's real costs are associated with building operations while the construction cost totals 10% (NRC, 2006); the majority of operational costs are related to heating, ventilating, and air-conditioning (HVAC), and illumination loads of buildings consume 40% of energy in the United States (EIA, 1995).

High-performance buildings reduce energy consumption significantly through utilization of high efficiency HVAC, lighting, and envelope systems. The Sustainable Building Task Report, examining 33 green building projects in California, confirmed that high-performance green buildings are 25% to 30% more energy efficient and demand, on average, 10% lower, peak electrical loads when compared to traditional buildings (Kats et al., 2003). Hartkopf et al. (2005) pointed the concept of the potential for buildings as power plants (BAPP), where energy efficient systems integrate with innovative, on-site energy generation systems. This concept is supported by a prediction that energy consumption in a BAPP would total only 11% of a typical US office building, and would offer first and lifecycle cost reductions and increased return on investment. An example case study for internal rate of return is the San Diego Ridgehaven Building that uses 65% less energy than its conventional alternative. This leads to a savings of $70,000 annually with a 57% internal rate of return (CIWMB, 2006).

High–performance green buildings also enable cost savings through improved maintenance (Kats et al., 2003). Even though actual financial benefits of operational and maintenance costs are yet to be quantified, minimal improvements in maintenance expenditures are known to produce considerable annual cost savings. Commissioning is a vital process that enables the systems to be installed and perform according to the design specifications (Kats et al., 2003). Use of efficient systems in the design combined with the commissioning process enables reduced operations and maintenance costs. While these potential savings are important, they are dwarfed, in comparison, by the potential benefits of improved environmental quality.

2.2.2 Indoor Environmental Quality

According to the U.S. Environmental Protection Agency and the American College of Allergy, Asthma & Immunology, Americans spend approximately 90% of their time within buildings (Morton, 2002). Indoor environmental quality in buildings, as defined by the US Green Building Council, comprises the combined effects of clean air, thermal comfort, appropriate light levels, natural light levels, and also views of the outdoors. Healthy indoor environmental quality (IEQ) is thus essential for individuals to maintain physical and psychological health. IEQ is also very important for business owners since their most costly item in United States is the salaries of employees which is, typically, about 70 times more than buildings' energy costs (BOMA, 1991). Poor quality building performance can reduce occupants' productivity up to 20% (Loftness et al., 2002). As a result, for employers, even minimal improvements in IEQ that increase employee's productivity can result in great savings that far outweigh investments in HPG buildings.

The Indoor Health and Productivity Project (IHP, 2001) catalogs over 900 papers on IEQ and occupant productivity. This growing body of research indicated that a high-quality indoor environment not only improves the productivity of employees, but also results in improved learning outcomes for students, decreases absenteeism, and can improve clinical outcomes in healthcare facilities. The combined impacts of these benefits potentially provide tremendous economic gains nationwide. Primary, empirical

IHP studies communicate an important message through collection of research on the relationships among different components of indoor environmental quality and occupant health and productivity. These studies, examined and summarized below, focus on the following areas: 1) HVAC system design and respiratory illnesses, 2) ventilation rates and occupant health, 3) IEQ, occupant productivity, and financial benefits, and 4) IEQ, daylighting and occupant performance.

HVAC systems are vital components of buildings that affect IEQ and occupant health. Sieber et al. (1996) performed a statistical analysis to explore the association between HVAC system design and communicable respiratory illnesses. The study suggested isolating outside intakes from potential pollutants through HVAC design and maintenance can result in a reduction in undesirable health outcomes.

The minimum requirement for ventilation for offices in the ASHRAE Standard 62-1999 satisfy 80% of the building's occupants and minimizes energy consumption within tolerable limits. This rate is controversial and has been investigated by various researchers. Seppanen et al. (1999) and Milton et al. (2000) studied the relationship between ventilation rates and productivity to understand the optimum ventilation rate for office buildings. Milton et al. (2000) demonstrated a positive association among increased sick leave and lower ventilation rates and humidification through a statistical analysis. This study also suggested that doubling the currently recommended ventilation rates would result in net savings of $15 billion in the U.S from increased productivity.

Fisk (2000) stated that improved IEQ can result in better health, increased productivity, and economic benefits in United States. The study examined the literature for the relationship among different indoor environment characteristics and acute respiratory illness, allergies and asthma, and sick building syndrome. The paper signified that even minor changes to temperature and lighting could lead to potential productivity gains which would generate annual productivity savings of billions of dollars, nationwide.

In 2003, Heschong Mahone Group (HMG, 2003) performed empirical research to examine the correlation between indoor environment and office worker performance. Significantly, two studies that examined workers in two different office settings established that improved view, ventilation, and air temperature conditions in the office spaces positively affected the productivity of the workers. Another empirical study performed by the same group (HMG, 1999) used test scores as a productivity indicator to assess student performance related to indoor environment. This investigation found that students' learning improved up to 21% in classrooms that received the most daylight when compared to the students who received the least. An overarching lifecycle study (Xenergy, 2000), involving three case studies for City of Portland, found that the buildings of focus would have produced savings between 13% and 16% from improved productivity and reduced operating and maintenance costs if the projects had been designed as HPG buildings.

The research summarized above shows that IEQ and its components, such as daylight, temperature, HVAC system design and maintenance, lighting levels and ventilation rates, affect occupant productivity. This crucial information for business owners and developers in the construction community highlights the need for high-performance green buildings.

The presented literature also demonstrates that energy considerations and indoor environmental quality are driving, business forces for owners and provide motivation to build high-performance green buildings. As a result, energy and indoor environmental quality attributes of high–performance green buildings are the focus of this research.

2.3 Building Environmental Assessment Systems

The emerging concern for a "green" environment created the necessity for developing criteria to evaluate the performance of green buildings and to establish levels of achievement for green building objectives. Building assessment systems established worldwide primarily intend to evaluate buildings at the product level according to criteria that define areas of sustainability or green attributes. In addition to quantifying the level of achievement, systems such as Leadership in Energy and Environmental Design (LEED) also aimed to increase the market demand for green buildings. Building assessment tools provide useful metrics to evaluate projects' sustainability performance. For example, LEED^{TM} rated buildings use an average of 30% less energy than those following nationally and locally required levels. US Green Building Council (USGBC) data on twenty-one LEED^{TM} rated buildings provide additional evidence that higher-level, certified buildings are generally more energy efficient than lower-level certified buildings (Kats et al., 2003). Although building assessment systems are useful tools to evaluate green building performance, several disadvantages, associated with the way they are designed, remain. These include: 1) consensus-based, variable weighting of the sustainability criteria, 2) ambiguous presentation of final rating that is not representative of project characteristics, and 3) a lack of project process based criteria that may contribute to the achievement of HPG objectives. Each shortcoming is explored below.

Building assessment systems provide criteria to evaluate sustainability performance of buildings and assign a consensus, based weighting these criteria. Limited scientific proof indicates that any one criterion in the building assessment systems affects the environment or the building's occupants more than the other. Therefore, weights assigned to the criteria in these systems differ in all of the environmental building assessment systems. For example, two US assessment tools Green Globes and LEED^{TM} use different weighting for energy use in the buildings among other sustainability criteria: one accounts for the 34% of total points, and the other for 29%, respectively (Kats et al., 2003).

Another consideration regarding building assessment systems is that most of these systems evaluate the buildings according to the sum of the points achieved by complying with their specific criteria. Exceptions to this, such as GBTool and Ecoprofile do exist; however widely used building assessment tools such as LEED^{TM} do not have a descriptive final evaluation of how the buildings perform in each criterion. As a result, buildings can be rewarded with high levels of certification from the total points they attain in these assessment systems, despite achieving little or no energy points, and/or limited expended effort for indoor, environmental quality categories.

Finally, building assessment tools focus on the product based performance metrics and do not fully appreciate projects' process related attributes. Widely accepted is that high-performance buildings require whole building design processes to fulfill performance requirements where key project participants work in an integrated fashion throughout the design processes (DOE, 2006). Therefore, management of the design process is vital for high-performance green buildings. The web-based assessment tool Green Globes^{TM}, distributed by Green Building Initiative in the United States, promotes value in the project management phase of the green building projects (GBI, 2006). However, a gap remains in the literature that quantifies the correlations between process and performance metrics. As a result, weighting of process criterion is also consensus-based similar to other metrics in Green Globes^{TM}, and is missing from most other building assessment tools. In a recent study, Magent (2005) attempted to characterize the design process for high-performance buildings, however process attributes and metrics to evaluate the high–performance, green building processes are yet, without definition.

This study reviews the building assessment systems in the United States and around the world and summarizes the most well known ones. The metrics used in these systems guided this study to the observation of common trends in building assessment systems and enabled development of performance and process based criteria.

2.3.1 Building Assessment Systems in the US

Leadership in Energy and Environmental Design (LEED) Green Building Rating System^{TM}, established in 1998 by US Green Building Council (USGBC), is a commercial building assessment tool that serves as a certification system for buildings in the US. It is primarily an assessment tool while it has value as a checklist for design and construction teams to learn how different strategies achieve certain levels of sustainability in a building. This rating system also acts as a market incentive since it has gained wide recognition by governmental institutions, business owners, and public. To date, LEED ^{TM} certified buildings, including commercial buildings and homes, total 1,230 units, worldwide, while the registered number of projects affirms a vast increase in the market with a total of 8,029 units (USGBC, 2006). The first LEED^{TM} certification, primarily developed for commercial office buildings, now has extension in which "practitioners have also applied the system to K-12 schools, multi-unit residential buildings, manufacturing plants, laboratories and many other building types" (USGBC, 2006). USGBC developed other certification types for other types of construction applications. These include: new commercial construction and major renovation projects; existing operations and maintenance; commercial interiors projects; core and shell development projects; residential buildings; and neighborhood development projects (in progress). Metrics used in the LEED^{TM} rating system are either performance-based (e.g., energy consumption, lighting levels) or prescriptive (e.g., compliance with ASHRE standards, use of low emitting materials). LEED^{TM} assigns points for each category from which users can select the criteria that they will attempt to achieve. These categories include: sustainable site development, water savings, energy efficiency, indoor environmental quality, and materials selection. The rating levels of LEED^{TM} are certified, silver, gold, and platinum. In this system, the buildings are rated according to the sum of the points that they achieved in each category (USGBC, 2006). Therefore, the final evaluation does not reflect how the buildings perform in each category or provide for setting a benchmark for a building's attributes.

Sustainable Project Rating Tool (SPiRiT) is an adaptation of LEED^{TM}, developed by the US Army. SPiRiT intends to integrate military requirements into LEED^{TM} and is suitable for use in the design process as a checklist for military users. The system includes additional criteria different than LEED^{TM}, categorized under the titles of facility delivery process, current mission, and future mission (Kibert, 2005).

Green Globes^{TM} is a web-based management and environmental assessment tool for buildings; it can be used to guide the integrated design process for green buildings and also as an assessment tool consisting of similar criteria as that of LEED^{TM} in regards to energy and environmental practices. The system is also used in Canada and United Kingdom; also its distinction from the other building assessment tools in the US is its process oriented criteria and project team-member, specific question setting that simplifies the application of the system (GBI, 2006).

2.3.2 International Building Assessment Systems

Building Research Establishment Environmental Assessment Method (BREEAM), initiated in 1990, is the primary building assessment system used in United Kingdom. BREEAM is one of the first widely accepted building assessment systems in the world for evaluating buildings according to an overall score, achieved from nine categories: management, energy (operational use), health and well being, pollution, transport, land use, ecology, materials, and water. The system's awards to commercial office, retail stores, residential, and industrial buildings is according to performance using certification levels of pass, good, very good, or excellent (Kibert, 2005).

Comprehensive Assessment for Building Environment Efficiency (CASBEE), an application, developed by The Japan Sustainable Building Consortium, evaluates eco-efficiency of buildings using four different tools: Pre-design (in progress), new construction, existing building, and renovation.

Green Star, a new building assessment system used in Australia, has its foundation in BREEAM and the LEED^{TM} criteria. The system primarily evaluates commercial office buildings' management of indoor environmental quality, energy, transportation, water, materials, land use and ecology, emissions, and innovation categories. The system refers to the sum of the achieved points in each category to assign an overall level of certification to a given building (Kibert, 2005).

Green Building Challenge's GBTool is intended to be used internationally. The system's scope is not limited to the level "building" but covers community considerations with sustainability criteria, primarily regarding resource consumption, loadings (e.g., green house gases, impacts on site), indoor environmental quality, and quality of service. The system uses benchmarks to understand the accomplishments of the evaluated buildings and presents achieved scores for each criterion (Todd et al., 2001).

Other international building assessment tools which will not be explained in detail include: EcoProfile (Norway), ESCALE (France), EcoEffect (Sweden), and The Hong Kong Building Environmental Assessment Method (HK-BEAM, Hong Kong) (Todd et al., 2001).

Reviewed literature offers a variety of US and international based whole building environmental assessment systems. Most of these systems are only product based, evaluating the performance at the building level while others also approach design process related metrics, environmental effects, and community related perspectives. The consensus among current classification systems of green building criteria include: classification of land use, water consumption, materials use, energy conservation, and indoor environmental quality criteria and their subcategories. Existing environmental assessment systems aids this current research in understanding and cataloging high-performance, green criteria for buildings. However, a gap remains in the literature for defining the relationships between process and performance metrics for high-performance green buildings. None of the presented systems include a full range of these criteria nor do they assign weight on the criteria based on rigorous quantitative analysis.

The following section reviews the project delivery literature to assemble process attributes for buildings and to ascertain the methods whereby study of the correlations between process attributes and performance metrics of building projects becomes possible. The next section also reviews case study based publications for green building projects to compile process attributes for high-performance, green buildings.

2.4 High-performance Green Project Delivery

Extensive research explores the effects and results of two main phases of a building project: 1) project delivery / pre-occupancy and 2) post-occupancy, as illustrated in Figure 2-3. Project delivery is a process that begins with the decision of an owner to construct a building and continues until the design and construction teams transfer the facility to the owner for occupancy. Preconstruction, design, construction, and commissioning activities take place during this process. Project delivery attributes influence a building project until project completion and occupancy. Decisions made early in the project delivery process such as building orientation or mechanical systems selection has the potential to greatly affect the ultimate building performance in the post occupancy phase. On the other hand, the effects of project delivery attributes on project performance outcomes at the end of construction, such as cost, schedule, quality, and safety are immediate concerns of the construction community; therefore, these have had wide investigation and verification through research (Sanvido and Konchar, 1999; Chan et al., 2002, Thomas et al., 2002; Ling et al., 2004). In addition to the effects of project delivery on project performance, the fact that owners and project teams can control them renders knowledge regarding project delivery attributes vital for building performance levels and of considerable interest to the construction community.

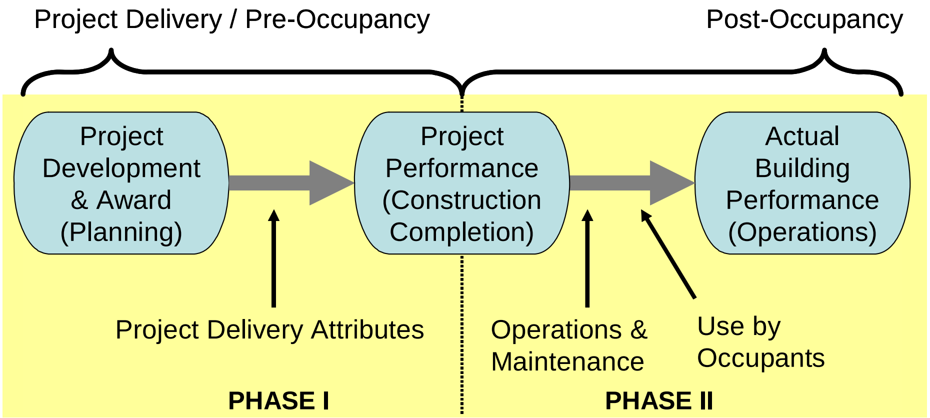


Figure 2-3: Evaluation elements of a building project

However, in the literature, a gap that examines the effects of project delivery attributes on high-performance green building project outcomes still exists. The process indicators and performance metrics of HPG building projects have been discussed in different studies and formats; however rigorous examination and definition of them is yet to be forthcoming. This section summarizes, from the literature, the existing project delivery and contractor selection research, characteristics of HPG building project delivery, defined process indicators, and performance metrics.

2.4.1 Project Delivery Systems in the US

The "Master Builder" system dates to the earliest structures built by humans and was widely used in the United States until the early 20th century. This term refers to a process by which buildings were designed, engineered, surveyed, and managed by a single master builder. This system only applies to the smallest building projects, since specialties in design and contracting are separate activities (Konchar and Sanvido, 1998). The lack of integration in the project delivery systems results in a lack of designer knowledge of construction. Yates and Baatersby (2003) proved the importance of gaining education of construction methods and processes for designers prior to starting a career. Based on evaluation of training at design firms, this study also uncovered a lack of construction knowledge. Along this deficiency, other gaps in familiarity with the project delivery process generated different types of project delivery systems which related and bound designers and contractors to owners by virtue of various types of contracts and processes.

Definitions of Project Delivery Systems

Three main project delivery systems are common in the United States: Design-bid-build, design-build, and construction management at risk. These project delivery systems, defined briefly below in the order that they evolved in the U.S. arise from existing definitions developed by Sanvido and Konchar (1999).

Design-Bid-Build: The owner holds contracts separately with the designer and the contractor. The contractor bids according to the construction documents completed by the designer. Design and construction processes take place sequentially in design-bid-build.

Construction Management at Risk: Similar to design-bid-build, the owner holds separate contracts with the designer and the contractor in this project delivery system. However; in this project delivery system the owner hires a construction manager to perform the pre-construction services. This construction manager cooperates with the designer, gives construction input in the design process, and mostly performs the construction activities. Depending on the completeness of the design documents, the construction manager can guarantee a price for the construction and start the construction activities while designing continues.

Design-Build: The owner contracts with one entity who is responsible for design and construction of the building. This project delivery system enables the contractor's input during the design process and allows initial construction prior to completion of detailed construction documents.

Effects of Project Delivery Attributes on Project Performance

Extensive work in the literature has attempted to understand the effects of project delivery attributes on project performance outcomes. Existing research studies comparatively investigate different project delivery systems, different factors of project delivery and performance outcomes regarding different types of projects (e.g., public and private) using different methods.

For example, three recent studies in the literature examined possible process indicators and potential performance metrics in the context of design-build project delivery systems. Through a survey of applications that resulted in 108 responses, a non-empirical study (Songer and Molenaar, 1996) identified owners' selection factors for a design-build project delivery system. Shortening duration ranked the first among the selection factors; large project size/complexity ranked last. The study also concluded that public and private sectors approach design-build selection similarly. Molenaar and Songer (1998) examined the correlations between possible process indicators (project, owner, market, relationship variables) and potential performance metrics (e.g., compatibility of budget and schedule variance with user satisfaction and expectations) in public sector design-build project selection through multi-attribute analysis on 112 sample projects. The study stated that all of the process indicators are significant for project success; however, the owner is the most important variable in the prediction models. Chan et al. (2002) studied 53 public sector design-build projects in Hong Kong and specified six project success factors from the results of a factor analysis. Multiple regression analysis, involving satisfaction with time, cost, quality of design, and quality of workmanship, identified three factors (project team commitment, client's and contractor's competencies) as significant predictors for successful project outcomes.

Two other studies in the literature present an extended scope that focuses on both private and public projects. These studies also conducted comparison analyses of design-build and design-bid-build project delivery systems. The first is an empirical study (Thomas et al., 2002) that compares the impacts of design-build and design-bid-build project delivery systems and observes significant differences in project outcomes with regards to cost, schedule, safety, changes, rework, and practice use (e.g., pre-project planning, project change management, team building, etc.). The study included statistical analysis using 167 domestic and international projects from the Construction Industry Institute (CII) Benchmarking and Metrics (BM&M) database. Overall the study showed that design-build project delivery system has a tendency to generate better performance outcomes.

The second extensive study (Ling et al., 2004) statistically analyzed collected data on 87 projects in Singapore. The study extended the scope of the previous comparative project delivery research, defined a wide range of variables, and examined the correlations between eleven possible useful project performance metrics and 59 possible process indicators for projects using design-build and design-bid-build project delivery systems. The study developed eleven prediction models through multivariate regression analysis. The most significant results show that gross floor area, contractor's design ability, and adequacy of plant and equipment are factors that affect delivery speed. Analysis of design-build project delivery systems indicated that flexibility on contract period during tender leads to slower delivery. For design-build projects, an important predictor for turnover and system quality proved to be contractor's previous experience.

The most inclusive study in this field, conducted by Konchar and Sanvido (1998), and based on statistical analysis using a large data set (316 U.S. building projects), compared the relative effects of design-build, design-bid-build, and construction management at risk project delivery methods on performance outcomes with regards to cost, schedule, and quality. With the focus on performance metrics, multivariate regression analyses performed on the data set proved that design-build project delivery system outperformed all others. The large, unbiased sample used for the study covering both private and public projects allowed presentation of reliable project delivery attributes supported by significant results. A summary of the results of this study appears in Table 2-2.

Table 2-2**:** Percentage of Average Difference between Project Delivery Systems by Performance Metrics (From Konchar and Sanvido, 1998)

Metric	DB vs. DBB	CMR vs. DBB	DB vs. CMR
Unit Cost	6.1 % lower	1.6 % lower	4.5 % lower
Construction Speed	12% faster	5.8 % faster	7% faster
Delivery Speed	33.5 % faster	13.3 % faster	23.5 % faster
Cost Growth	5.2% less	7.8 % more	12.6 % less
Schedule Growth	11.4 % less	9.2 % less	2.2 % less

Note: DB=design-build; DBB=design-bid-build; CMR=construction management at risk

The study also provides guidelines for the construction community regarding project delivery processes such as procurement method, team, and contract type selection. Sanvido and Konchar (1998) also made comparisons between this empirical study and other similar studies in the literature. The University of Reading Design and Build Forum's study (Bennett et al., 1996) served a basis for the Sanvido and Konchar's study. Bennett et al. (1996) compared design-build and design-bid-build project delivery systems using statistical techniques based on more than 170 projects in U.K. and developed similar results. Both studies not only provided significant results related to project delivery systems, but also showed that other critical project delivery attributes can affect project performance (Sanvido and Konchar, 1999). The significant results of this seminal research, indicating design-build as the best performing project delivery system, have subsequently led the construction research community to study specific factors of design-build.

Different from empirical studies, for project delivery and contract strategies (PDCS), Oyetunji and Anderson (2001) developed a decision support tool that focuses on the owner's priorities, objectives, and resources regarding the project. The tool enables users to select specific considerations and priorities within the project on an Excel^{TM} format; then, it assigns weights to the related factors, quantitatively evaluates the twelve PDCS combinations, and offers one of them as a result. An early project delivery selection system (PDSS) was also a development of Vesay (1992) whose efforts were one of the first to clearly articulate the variable choices and outcomes of project delivery methods.

Summary of Project Delivery Methods

Reviewed literature demonstrated the impact of project delivery systems and process indicators on project performance outcomes and that use of design-build project delivery system has increased in the recent years. The literature explains this trend change in the construction industry by the fact that design-build project delivery systems outperform other systems. A gap remains in the literature: a lack of consideration of a similar approach for high-performance, green buildings. The current research intends to fill this gap by combining existing variables with additional HPG project specific variables to determine project delivery processes, performance outcomes, and the relationships among them.

The literature review also demonstrated the interchangeable use of factors, indicators, outcomes, and metrics in defining similar instances. A need remains for refined language in this area. Therefore, “process indicators” and “performance metrics” will be used in this study to define the process factors and project outcomes in the project delivery processes.

2.4.2 Procurement of Construction Services

The important role of teams and experience in project outcomes defined in existing research indicates that project procurement (also referred to as contractor selection), is important to the success of project delivery. The construction industry has long been dominated by a low-cost mind-set for the contractor selection process. However, recent research showed that project specific criteria have also become important in the contractor selection process for both public and private sector enterprises (Wong et al., 2000).

Upon realization of the project specific criteria's importance in contractor selection process, research studies have developed and validated models and methods to select the best procurement method and most suitable contractor for a given project's characteristics (Alhazmi and McCaffer, 2000; Fong and Choi, 2000; Palaneeswaran and Kumaraswamy, 2000; Sonmez et al., 2001; Mahdi et al., 2002). Holt (1998) conducted an overarching study which considered a different methodology to select the contractor.

The qualifications of contractors that owners mostly consider in the prequalification and bidding process are financial stability, technical capabilities, health and safety performance, and management abilities (Hatush and Skitmore, 1997). Contractors' perspectives of the prequalification criteria parallel owners' perceptions (Jennings and Holt, 1998).

Performance of Different Procurement Systems

Gransberg and Senadheera (1999) compared three different procurement methods in the design-build project delivery system for transportation projects: low-bid, adjusted score, best value. The study concluded that each method can be valid for different types of projects; the important factor being evaluation of projects' necessities. Conversely, Molenaar and Gransberg's case study (2001), researching design-build selection for small highway projects, stated that both cost and schedule improved with two-step procedures. A two-step procedure is a system in which owners filter design-build entities according to their responses to a request for qualification (RFQ) documents as the first step followed by an evaluation process dependent on technical and cost based proposals. This study illustrated the price and qualitative considerations that lead to procurement methods as shown in Figure 2-4.

Molenaar et al. (1999) also confirmed, through a quantitative analysis of 104 completed public sector design-build projects, that two-step procedures perform better than one-step procedures or qualifications based procedures using both schedule and cost metrics. In summary the findings are as follows: Two-step procedures produced projects 1% closer to budget than one-step procedures, and 2.6% closer to budget than

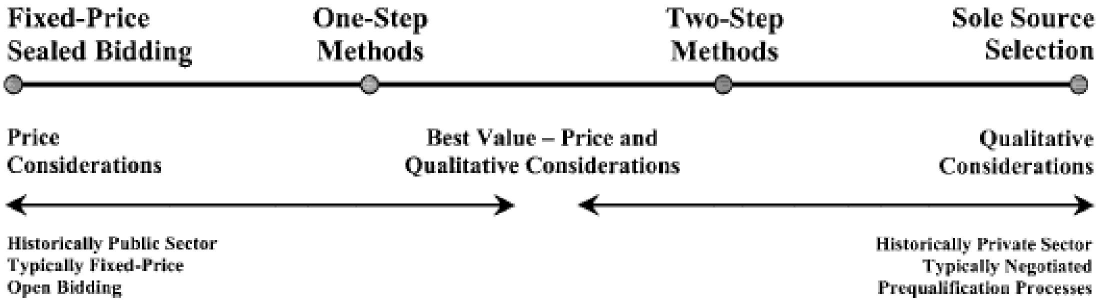


Figure 2-4: Selection Methodology Continuum (Molenaar and Gransberg, 2001)

qualifications based procedures. Also, two-step procedures produced scheduled project completion 1.5% faster than either of the two alternatives. A recent quantitative study examining 76 U.S. projects for design-build procurement systems (El Wardani et al., 2006) proved that the qualifications based selection method leads to lowest cost growth when the low bid procured projects generated the highest cost growth. Although statistically not proven due to limited sample size, this study states that none of the procurement methods outperformed any other factor regarding cost and time performance metrics for a design-build project delivery system. Procurement methods classification used in the study conducted by Beard et al. (2001) mostly reflects current applications in the industry. Therefore, this classification is also used in the current research**.**

Classification of Project Procurement Methods

El Wardani et al.'s study (2006) provides five categories of procurement methods, which the current research uses after adaptation from Beard et al. (2001). These methods include:

1) Sole Source Selection: Owner directly selects the service provider based on existing relations, past performance, technical abilities, administrative qualifications, and reputation. Lack of price competitiveness (Molenaar and Gransberger, 2001) is a disadvantage of this method while a shorter procurement timeframe makes it attractive (El Wardani et al., 2006).

2) Qualifications based selection: Owner evaluates the candidates according to their responses to RFQ. Criteria used in the RFQ depend on past performance, technical

and administrative qualifications, reputation, and financial strength (Beard et al., 2001). Negotiated contracts are a preference in this procurement method to ensure better performance.

3) Best value selection: In this method, the service provider responds to the owners request with a combination of cost and technical proposals for the project (Beard et al., 2001). Owner assigns weight to each criterion according to the organization's perspective of importance and has the ability to evaluate both qualifications and price with this method.

4) Fixed Budget/Best Design Selection: Selection of the service provider is based on the technical and qualitative scopes of their proposal since the budget is a given from the owner's RFP (Beard et al., 2001).

5) Low Bid Selection: The selection is based on the lowest cost in the proposals. However, this method requires the highest degree of design documentation completion at the time of bidding (Molenaar and Gransberger, 2001).

In addition to the list above, competition is another procurement method used in the selection of a design team based on design excellence.

2.4.3 Characteristics of High-performance Green Project Delivery

The HPG project delivery process is different from traditional project delivery; hence, a lack of understanding of HPG project characteristics is likely to lead to high project costs (Smith, 2003). The particular characteristics of HPG project delivery reviewed in the literature includes: owner's commitment to HPG characteristics, integrated design, team experience, design coordination and documentation, timing of project participants' involvement, and use of energy simulation tools early in the design process.

An owner's commitment to high-performance green features is crucial for HPG project success. Process maps that Lapinski et al. (2006) generated for Toyota Motor Company's project delivery practices showed that early integration (even at the capital budgeting phase) of high-performance green objectives generate highly performing, green buildings without a cost premium. Beheiry et al. (2006) supports this view by concluding that "corporate commitment to sustainability at the executive level translates to better planning for sustainable project practices at the project definition level" and can generate better cost and schedule outcomes.

Integrated design is essential for achieving best performing buildings within reduced budgets. HPG projects necessitate integrated design processes with interdisciplinary collaboration and increased interaction and cautious materials and systems analysis starting early in the design process (NIBS, 2005; Riley et al., 2004). Decisions important for a building's performance such as building orientation, mechanical systems optimization, daylighting and envelope design are mostly made early in the design process. As the design proceeds, it gets more difficult to change these features of buildings which may result with less optimal building performance in the case of traditional building design processes. Yudelson (2008) using the illustration below in Figure 2-5 describes that opportunities for integrated design diminishes as time proceeds within a project.

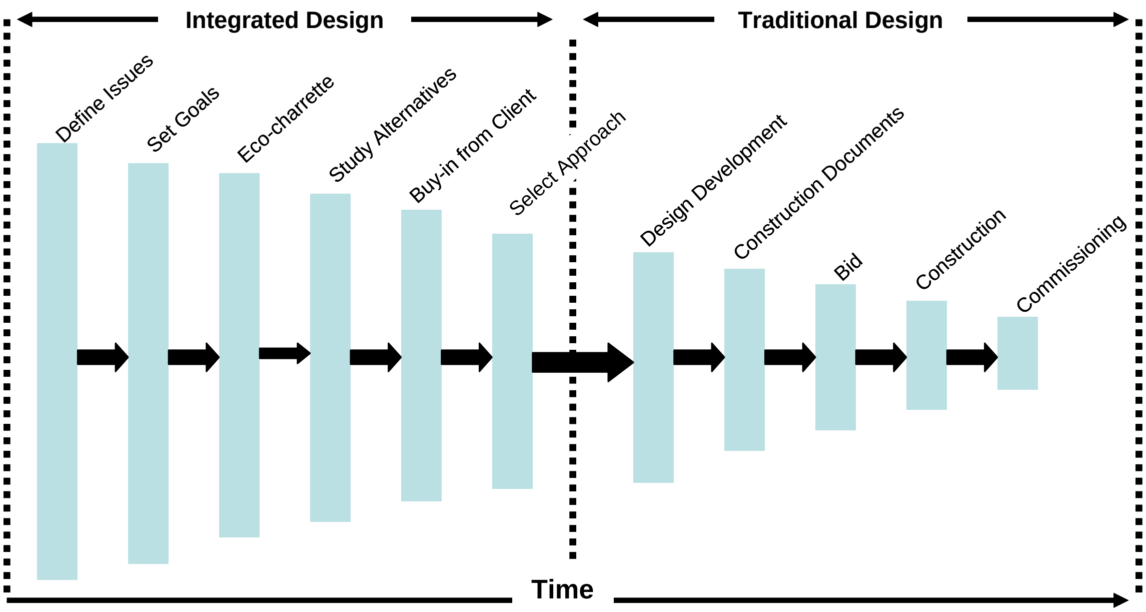


Figure 2-5**:** Opportunities for utilizing integrated design benefits are higher in early design phases of building projects.

Therefore, experienced integrated design teams are more likely to enable superior project outcomes for HPG building projects (GSA, 2004; Lapinski et al., 2006).

Common mistakes observed in HPG project delivery that impact the project performance are: 1) Adding green features to a traditional building halfway through the process, 2) Non-integration of green features to a building design, 3) Lack of energy consultant's integration in the design process starting at the early stages (Riley and Horman, 2005), 4) Under utilization of energy strategy and simulation tools early in the design process, 5) Lack of understanding and communication for prerequisites of key design decisions, and 6) Lack of constructability knowledge in the design process (Horman et al., 2006). Reviewing the literature will help define project delivery success factors for HPG building projects.

2.5 Project Delivery Success Factors and Performance Outcomes

Extensive research examined success factors contributing to project performance outcomes. A great amount of this research investigated these variables in the context of design-build projects. Songer and Molenaar (1996) analyzed owner selection factors for design-build project delivery systems including shortened duration, established cost, reduced cost, constructability/innovation, established schedule, reduced claims, large project size and complexity. They presented the relations of project characteristics and project success criteria in another study a year later. The variables from the Songer and Molenaar study appear in Table 2-3**.**

Chan et al. (2001) studied project team commitment, contractor's competencies, risk and liability assessment, client's competencies, end-user's needs, and constraints imposed by end-users for time and cost success. El Wardani et al. (2006) examined procurement methods, factors for contractor selection, contract type, incentive clauses, form of specifications, contractor and subcontractor selection processes, and timing of selecting subcontractors for cost, and schedule success.

Table 2-3: Project Characteristics and Success Criteria in Public Sector Design-build Projects*

Appropriate Project Characteristics		**Project Success Criteria**
Well defined scope	Current state–of-the-market	On budget
Established budget	Availability of designers/builders	On schedule
Established completion date	Size of project	Meets specifications
Standard design specifications	Type of contract	Conforms to user's expectations
Technologically advanced	Shared understanding of scope	High quality of workmanship
Owner's construction sophistication	Alternative financing options	Minimize construction Aggravation
Owner's willingness to forego design input		

*from Songer and Molenaar, 1997

Chan et al. (2002) conducted an extensive review of literature focusing on project success criteria of design-build projects and collected them for the illustration given in Figure 2-6.

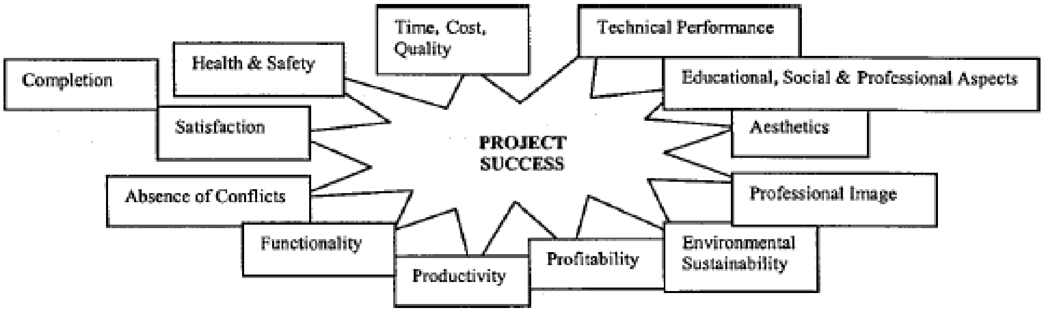


Figure 2-6**:** Criteria for design-build project success (Chan et al., 2002)

Recently, Chan and Chan (2004) extended the scope of success factors of a construction project and classified these factors according to under project and human related factors. This study also added an external environment, project management actions, and project procedures into the framework for project success.

CII’s BM&M database version 7.0 includes cost, schedule, safety, changes, rework, and productivity regarding performance metrics, and pre-project planning, constructability, team building, zero accident techniques, project change management, design/information technology, materials management, planning for start-up, and quality management regarding practice use metrics (Thomas et al., 2002).

Other studies in the literature also identify relations between process factors and performance outcomes for other delivery systems: Ling et al. (2004) examined a variety of project success factors along with performance metrics such as cost, time and quality for design-build and design-bid-build projects. Konchar and Sanvido (1998) performed an empirical study focusing on an extensive number of descriptive and quantitative variables for project cost, time and quality performance for design-build, design-bid-build, and construction management at risk project delivery systems.

A consensus exists for several performance metrics and process delivery indicators. However, the performance metrics used in Konchar and Sanvido's (1998) study, such as unit cost, delivery speed, and turnover quality, are the prior performance outcomes that are of most interest to the owners. Lessons learned from similar studies, especially the project indicators, performance metrics, and the questions within the data collection tool of Konchar and Sanvido's (1998) and El Wardini's (2006) studies guided the current research.

Very little research appearing in the literature considers the causal relations between process indicators and performance outcomes for green projects. Beheiry et al. (2006) hypothesized that commitment to sustainability at the top management level followed by good practices at the time of construction project planning leads to high project success in means of cost, schedule, design changes, and safety. This study developed possible management and construction practice indicators under three pillars of sustainability: economic development; social development; and ecological development.

Actual building performance as a reliable way to measure building performance levels has received emerging attention. Pacific North National Laboratory (Fowler et al., 2005), Environmental Protection Agency's Energy Star Rating System (EPA, 2006), US Department of Energy (DOE, 2006), and recently, Green Building Alliance (GBA, 2006) generated metrics regarding building performance at the post-occupancy phase, previously illustrated as Phase II in Figure **2-3**, for the areas of energy (e.g., annual energy, electric, gas, renewable energy), utilities (water use, sewer cost), operations and maintenance, health, recruiting and retention, and property demand. However, obtaining data of these metrics is extremely difficult due to lack of facility managers who record these statistics, and their (un)willingness to share them. Mechanisms that attempted to collect this data, unfortunately, have a significant non-response rate.

2.6 Green Building Databases in the US

Delivery of high-performance green buildings is a life-learning experience for project teams since the green market is fairly new, the first cost and life-cycle costs/benefits of these buildings are just being explored and sustainable practices and technologies are evolving. Web-based database systems of green building case studies provide a format for the construction industry to learn from other project teams green building design and construction experiences.

Existing green building databases are particularly important for the current research for several reasons: 1) To understand the important process attributes for green building project success, 2) To review the type of metrics from which databases are collecting case study data, 3) To observe the attainable data regarding different types of process indicators and performance; 4) To learn the effective ways to collect data on study metrics, and 5) To make a list of potential case study projects from which to collect data. The following sub-sections review and summarize existing green building databases in the US to gain a greater understand of the previously listed reasons.

US Green Building Council's Green Building Database (USGBC, 2006): This database provides a list of the projects that received LEED^{TM} certification and registration in the system. The data includes owner, location and certification level information. The database also provides the final checklist showing the achieved points within the attained certification level.

Department of Energy's High-performance Buildings Database (DOE, 2006): This database, developed by the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL), is a central repository of in-depth information and data on high-performance, green building projects across the US and Canada. Currently the database includes 91 projects with submitted data of developed metrics. These metrics include: design strategies; procedures and actual performance data on energy and lighting use; environmental performance; materials consumption; design process; delivery; and finances. The developed metrics and the survey, as the data collection tool of this system, attempt to capture, quantitatively, the level of consumption for defined criteria (e.g., consumption of resources such as net land use, renewable energy consumption for building operations, and net annual potable water use; effects on atmosphere air quality, such as estimated ozone depletion that building operations cause, and solid waste disposal in tones/m^2) as key performance indicators. Also captured are cost of construction and costs for operations and maintenance. In summary, this database attempts to cover a wide range of project processes and post-occupancy performance metrics to derive lessons learned for high-performance project delivery processes. However, the database does not consist of important delivery attributes such as project procurement data, contractual relationships, and involvement of project participants in the process. Moreover, definition and categories of project delivery systems within the database are defective. Most importantly, due to the detail of the questions and the design of the data collection tool within this system, the response rate for the questions submitted for the projects is very low.

Davis Langdon Knowledgebase (Davis Langdon, 2006): This database stores information about each project, such as estimate phase and date, inclusions and exclusions, and construction conditions. However, the main focus of this database centers on the collection of component cost information for the projects. The database contains information from nearly 600 distinct projects in 19 different states for a wide variety of building types and programs. Construction costs and design parameters of all of these projects are tracked including quantitative measures, specific sustainability measures, LEED^{TM} points targeted, or achieved. This database is not available to the public.

California Sustainable Building Case Studies (CIWMB, 2006): The projects identified in this database highlight some of the most innovative applications of sustainable building technologies, equipment, and systems as well as project information, such cost and location. The data base includes forty projects along with their project team contact information.

North Carolina Green Building Technology Database (NCGreenBuilding, 2003): This database includes 77 projects, and assists locating projects in North Carolina that have implemented specific green building strategies or technologies. The database includes contact information for the projects, as well as an explanation of applied sustainable practices within the projects.

The presented databases mainly provide a list of green buildings with minimal data on the specifics of the projects. The DOE database is an exception as it is the most comprehensive system with developed performance and process metrics and a designed data collection tool. These databases provide a source of green projects to be included in the research data collection phase of the current research. The DOE post-occupancy focused performance metrics do not apply to the current research; however lessons learned from this database in terms of survey application strategies to achieve a larger response rate will be of assistance.

The literature review of high–performance green building databases confirmed the need for a database providing information on project delivery processes and performance metrics that utilizes effective survey application strategies to streamline the project submission process. This database can enable assessment of larger numbers of case studies which would lead to significantly higher levels of statistical analysis of correlations between high-performance green project processes and performance levels, as well as a format for displaying, for the construction community, the lessons learned from case studies.

2.7 Summary

HPG buildings are desired by business owners due to energy efficiency and the high indoor air quality they maintain. The decisions important for HPG building project performance are made early in the project delivery processes. Based on the reviewed literature, a need exists for research for the construction community that explains project delivery process indicators contributing to better HPG building project performance. Due to a lack of process guidelines to be utilized during the project delivery processes of HPG building projects, it generally gets too late in the delivery process for project teams to achieve the set project goals. This study intends to fill this gap by defining process indicators and performance metrics for HPG building projects and examining the causal relationships between them. This study also captures lessons learned from existing green building databases in pursuit of assembling effective process indicators and data collection application strategies. The next chapter describes the methodology employed to realize the goals of the current research.

Chapter 3

Methodology

3.1 Introduction

The literature review revealed the need for a study that defines the attributes of project delivery processes that lead to best performance outcomes in high-performance green (HPG) buildings. The current literature offers product-based high-performance metrics as a part of existing building assessment systems (e.g., LEED® and Green Globes™), but lacks descriptive process indicators and fails to present the relations between delivery process attributes and performance outcomes for HPG buildings. Therefore, the research question this study posed is: “What project delivery attributes relate to performance outcomes in HPG building projects?” To answer this research question, this pilot study explored meaningful evaluation metrics for HPG building project delivery. The research also built the foundation for rigorous HPG delivery research with its contributions to data collection and analysis methods.

This research is a first step in its field and exploratory in nature due to: (1) The extensive number of variables with a potential impact on the HPG project performance; (2) The lack of rigorous research on green building projects in the literature; (3) The green market being in its infancy with a limited population; and (4) The challenges of data collection in this field; and (5) The immaturity of the learning curve for the evolution of green design and building practices. The research strategy selected to achieve the research goals was a mixed-method strategy that combines quantitative and qualitative methods. The research employed a “QUAN- Qual approach” as defined by Gay and Airasian (2005) that started with a quantitative analysis examining a pool of HPG project delivery data collectively to screen the meaningful evaluation metrics, and then continued with a qualitative analysis to triangulate the findings of the quantitative analysis and enabled additional lessons to be drawn from case studies. This chapter contains a description of the research process and specific methodological steps followed in the investigation of the research question.

3.2 Research Goals and Objectives

The main goals of this research study were to: (1) Define meaningful evaluation metrics for HPG building project delivery; (2) Develop tools/methods to collect HPG building project delivery data; and (3) Illustrate data analysis methods for HPG building project delivery research. The specific objectives of this study were to:

1) Articulate project delivery attributes and evaluation criteria for performance outcomes in HPG building projects;
2) Develop, test and verify a tool for obtaining data on HPG delivery attributes and performance outcomes;
3) Perform data collection on identified building projects;
4) Examine the collected data using mixed methods to identify the HPG building project delivery evaluation metrics; and
5) Refine the results, summarize research contributions, and make recommendations for future research.

3.3 Research Process

The literature review guided the development of the methodology for this research and the description of the steps taken in this study. The research process and steps followed are listed in Table 3-1, including the chapters in which these steps are presented. The research steps include review of relevant literature, selection of a research strategy, data collection tool development, data collection, quantitative and qualitative data analysis steps and results, and conclusions.

Table 3-1: Research Process and Steps

Research Process	**Steps**
1. Review of Relevant Literature (Chapter 2)	* Conduct Literature Review * Document Relevant Project Delivery Metrics, Data Collection and Analysis Methods, and Sources for Data Collection
2. Selection of the Research Strategy (Chapter 3)	* Review Research Characteristics - Conduct a Power Analysis to Illustrate Project Delivery Research Characteristics * Select Mixed Method (QUANTITATIVE-Qualitative Approach) as the Research Method * Explain the Type and Components of the Research * Identify the Unit of Analysis
3. Development of the Data Collection Tool (Chapter 4)	* Evaluation Metrics for HPG Building Project Delivery - Independent Variables (Process Indicators) - Control Variables - Dependent Variables (Performance Outcomes) * Preliminary Survey Design * Survey Verification
4. Review of the Expected Research Outcomes (Chapter 3)	* Explain the Expected Research Outcomes - Evaluation Metrics - Process Indicators - Data Collection Tool
5. Data Collection Procedure (Chapter 5)	* Define the Study Population Characteristics * Describe the Procedures to Collect Data * Report Study Response Rate * Explain the Steps to Record and Standardize the Collected Data * Explain Tactics to Increase the Data Quality - Sampling Error - Response Bias - Non-response
6. Quantitative Data Analysis (Chapter 6)	* Define the Procedures for Analyzing the Data * Perform Statistical Data Analysis and Document Results - Univariate Analyses: One-way ANOVA and Regression - Multivariate Analyses: Analysis of Covariance * Conduct Power Analysis to Predict Sample Size for Future Research
7. Qualitative Data Analysis (Chapter 7)	* Define the Procedures for Analyzing the Data * Describe the Tactics to Satisfy the Research Design Quality Criteria * Collection of Case Study Data - Collect Evidence - Create a Case Study Database - Maintain a Chain of Evidence * Case Study Evidence Analysis - Identify the Logic to Link the Data to the Propositions - Define the Criteria for Interpreting the Findings - Document Results
8. Summary and Conclusions (Chapter 8)	* Summarize Findings of the Study * Identify Research Limitations

3.3.1 Literature Review

The literature was reviewed to meet the objective of articulating project delivery attributes and evaluation criteria for performance outcomes in HPG building projects. As presented in Chapter 2, the literature review showed that the design-build delivery system has been widely used in the construction community in recent years and has outperformed other project delivery systems in both public and private sectors. The literature review also presents key features in project delivery processes other than the selection of project delivery systems that can affect project performance outcomes.

Recent research conducted at the Pennsylvania State University regarding project delivery and procurement methods (Konchar and Sanvido, 1998; El Wardani et al., 2006) guided assessment of project delivery attributes such as project delivery systems, procurement methods, contract types, and team characteristics. The literature also helped the researcher to define additional attributes of HPG project delivery, including owner's commitment, timing of project participants' involvement, integrated design, and construction application procedures.

In addition to the assembly of a list of HPG project delivery attributes, the literature review also helped the researcher to understand the ways to measure the effects of delivery attributes on HPG project performance. Time, cost, quality, and safety were found to be the most accepted project performance metrics in the literature. A review of existing building assessment systems provided guidance in the identification of high-performance levels as an additional potential metric for measuring performance outcomes in HPG buildings. The project delivery indicators and performance metrics collected are documented in Chapter 2 and described in detail in Chapter 4.

Assessment of performance metrics is followed by a review of systems for capturing relevant data on HPG building projects. A review of existing database systems proved to be a useful source of information on green and high-performance green buildings. This review also pointed out the need for a system that can collect, present, and allow learning from HPG building project delivery data on descriptive project delivery process indicators.

Lastly, the literature, more specifically studies conducted by Konchar and Sanvido (1998) and El Wardani et al. (2006), provided a foundation for the development of a data collection tool for HPG building project delivery. The literature review revealed different research methods that were utilized in similar efforts in the construction industry to better understand building project delivery processes. Survey applications and quantitative data analysis techniques were found to be the most often-used research methods in data collection and analysis in similar research efforts (Molenaar and Songer, 1998; Konchar and Sanvido, 1998; El Wardani et al., 2006).

Overall, the literature review helped in: (1) Establishing comprehensive background on high-performance green building project delivery research; (2) Assembling project delivery process indicators and performance metrics; (3) Identifying the need for research on poorly defined HPG project delivery process attributes and investigation of new variables in the delivery process; (4) Defining the need for a data collection tool and methods; and (5) Providing an understanding of data analysis methods used in similar research efforts. The literature review was followed by the selection of a research strategy.

3.3.2 Selection of the Research Strategy

This study examined the impact of the project delivery attributes on project performance outcomes in HPG buildings as illustrated in Figure 3-1 and focused on defining meaningful evaluation metrics for HPG building project delivery. According to the literature, the approach for understanding the associations between project delivery attributes and performance metrics is to use quantitative techniques. However, this research strategy often results in low levels of certainty due to the unique characteristics of building project delivery research, where many variables can contribute to perceived success or failure and a broad array of project performance outcomes.

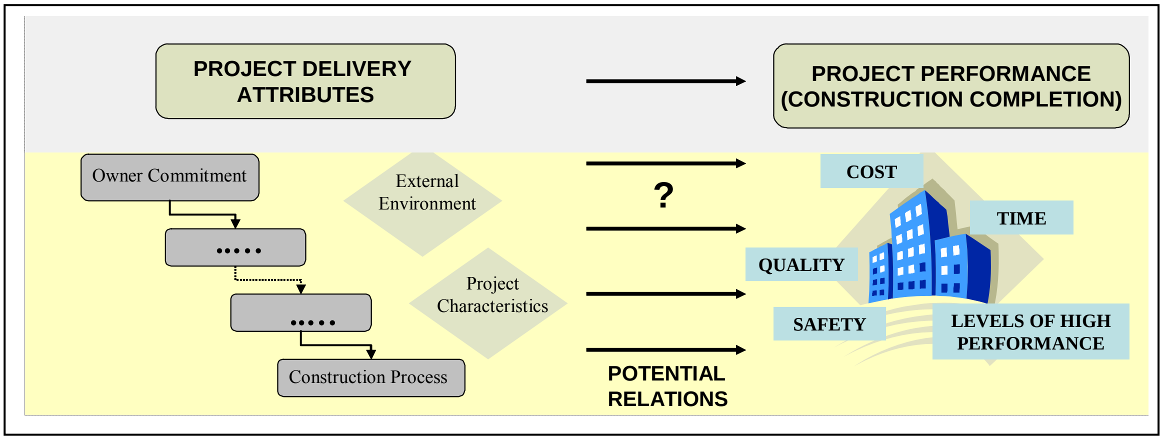


Figure 3-1**:** High-performance green project delivery research

Research Characteristics

In the literature, quantitative research has been conducted on the correlations between project delivery attributes and performance outcomes. However, the majority of the explanatory approaches in construction research fails to explain significant relationships between project delivery attributes and performance outcomes due to: (1) the extensive number of project delivery attributes that can affect project performance outcomes; (2) the variety of characteristics in the unit of analysis in construction research—the building projects—that reveal great variation in performance outcomes (e.g., unit cost). The variety of building project characteristics are related to the variety of types of facilities (e.g., office, healthcare, residential, laboratory, education), types of construction (e.g., new construction, renovation, tenant improvement), levels of project complexity, and differing priorities and perceptions of success and failure by different project owners.

Use of large sample sizes is one remedy for these problems in quantitative research. The importance of sample size in quantitative research is illustrated in the utilization of a power analysis example in Appendix A. This analysis—conducted on real construction data collected for project delivery research at Penn State (Konchar and Sanvido, 1998)—shows that large sample sizes in building project delivery research are required to achieve convincing levels of significance in the quantitative analysis results.

However, the challenge of collecting construction field data, coupled with restrictions in the current green building market in terms of the limited number of completed green buildings and exemplary projects, inhibits the creation of an ideal sample size. The study described here proposed to include descriptive process indicators in the HPG project delivery research in addition to the important metrics located in the literature to identify best practices that could lead to improved performance in HPG building projects. This research study is pioneering and has provided an even larger set of variables for investigation. Therefore, quantitative techniques are necessary but not sufficient for this study to achieve its main goals.

Selection of Research Methods

Zimmerman (2005) indicated that quantitative research is objective while qualitative research is subjective because it includes beliefs and individuals. Together, these methodologies can provide comprehensive insight into a research problem (Zimmerman, 2005). Recently, especially in the social sciences where one type of research methodology is not adequate for responding to a research question, researchers are combining quantitative and qualitative research methods. This combination, also known as mixed-method research, involves three different approaches (e.g., QUAN-qual, QUAL-quan, quan-qual) in which different weights are placed on quantitative and qualitative research methods to jointly answer the same research question (Gay et al., 2005).

The research characteristics explained above affirm the use of mixed methods in this study to achieve the research goals. Quantitative analysis methods are necessary in this research to screen the meaningful HPG project delivery evaluation metrics. On the other hand, qualitative methods should also be utilized to support the findings of the quantitative analysis and draw additional lessons from the limited number of exemplary projects within the study sample.

Therefore, this study employed a QUAN-Qual model, as explained in Gay et al. (2005), in which the research began with a quantitative data collection and a hypothesis-testing procedure. The second phase involved qualitative data collection, analysis, and interpretation, and the elaboration of findings from the first phase. The procedures followed and their outcomes in each step of this research are illustrated in Figure 3-2

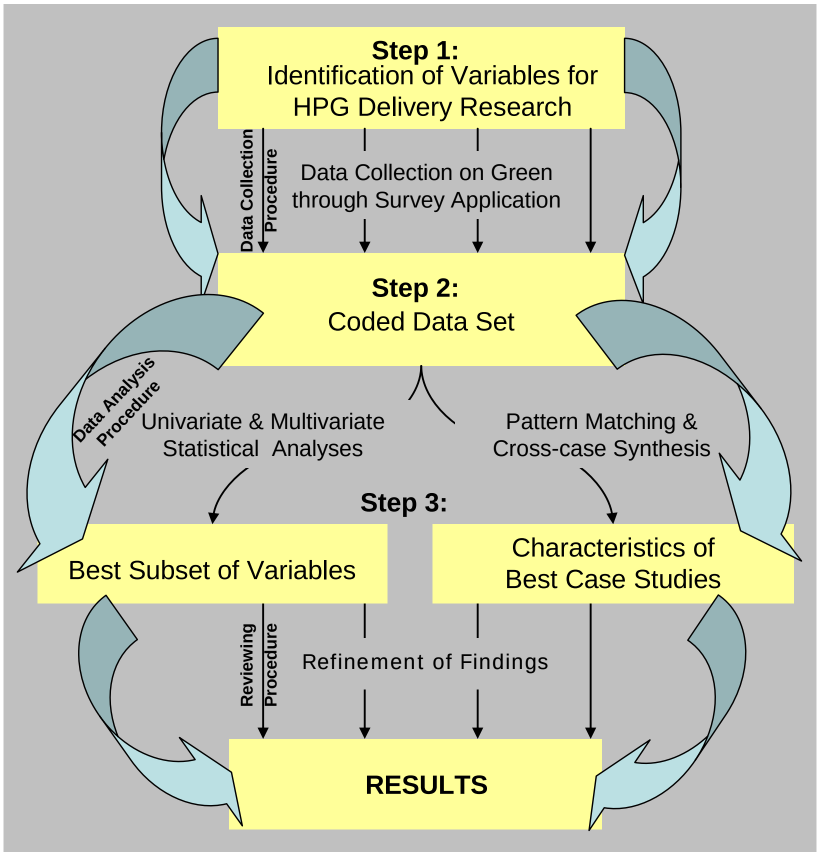


Figure 3-2**:** Process map for the HPG project delivery research methodology

The Type and Components of the Research

Yin (2002) suggested that three conditions navigate research: 1) The type of research question; 2) The investigator's control over the behavioral events; and 3) The degree of focus on historical or contemporary events. After identifying these conditions, a researcher can decide to pursue exploratory, descriptive, or explanatory approaches.

This study mainly posed a "what" question that specifically looked for process indicators in HPG building project delivery: "What project delivery attributes relate to performance outcomes in HPG building projects?" The study did not require control over behavioral events or a focus on history. Therefore, the research strategy involved following an exploratory approach that employed a mixed-method procedure.

The Unit of Analysis

The analyses in this research were accomplished on a variety of projects to satisfy the research goals. The project delivery attributes that led to best performance outcomes in HPG buildings were learned from different projects owned, designed, procured and constructed by different individuals, teams, and organizations. In other words, "*projects*" were the unit of analysis in this study, rather than organizations or individuals.

The research strategy section of this chapter includes a description of the identification of the research characteristics, selected research methods, type of research, and unit of analysis. Overall, the research aligned with the purposes of exploratory research and followed a mixed-method approach that utilized quantitative and qualitative types of analyses. Data collection tool development is next described as the next step in the research methodology.

3.3.3 Data Collection Tool Development

A set of activities were performed to meet the second objective of this study: To develop, test and verify a tool for obtaining data on HPG delivery attributes and performance outcomes. First, the evaluation metrics for HPG building project delivery were assembled and categorized based on the literature review. Second, a survey was developed as the data collection tool for this research. Specific questions were designed to address the HPG project delivery evaluation metrics for this research. Third, the survey was presented at the Partnership for Achieving Construction Excellence (PACE) Roundtable in 2005 and received industry professionals' feedback. A pre-study was then conducted to obtain more comprehensive feedback on the survey. The survey was finalized after this pre-study phase. The steps followed to develop the data collection tool are described in detail in Chapter 4.

3.3.4 Expected Outcomes

The theoretical background and the pre-test of the survey enabled the development of expected outcomes in this study. The majority of the expected outcomes (EO) address the effects of project delivery process indicators on performance metrics of HPG building projects in terms of *cost, time, quality, high-performance levels,* and *safety,* while the others relate to control variables and the efficiency of the developed data collection tool and methods:

EO # 1—Evaluation Metrics: The defined project delivery attributes can influence project performance outcomes in HPG building projects. Seven process indicators (PIs) and control variables were defined for this research (see Chapter 4). Expected research outcomes for each of these project delivery attributes are as follows:

PI #1—Owner Commitment: An owner who is committed to high-performance green features is likely to follow a better delivery process by introducing "green" concepts early in the project; leading project teams in the right direction to integrate green features into the design rather than treating these features as adds-on to the project; and facilitating necessary resources that lead to better HPG project performance outcomes.

PI #2—Project Delivery System: The design-build project delivery system leads to the best HPG project performance outcomes.

PI #3—Project Procurement: Considering a diverse set of criteria such as past experience of teams and technical aspects of a proposal when selecting project teams contributes positively to HPG project performance outcomes as opposed to focusing only on lowest bid in the selection of the project teams. These conditions also apply to mechanical and electrical subcontractors in HPG building projects.

PI #4—Contract Conditions: Owners can achieve their specific project goals in HPG buildings by including goal-specific language and conditions in contracts with project team members.

PI #5—Integrated Design: Early involvement of key project participants (e.g., designer, contractor, energy and lighting consultants, commissioning agent, green design coordinator, mechanical and electrical subcontractors) in the HPG project process and high interaction between these participants in the design process contribute positively to achieving the goals of a HPG project.

PI #6—Project Team Characteristics: Project teams' past experience and team communication contribute positively to the success of HPG projects.

PI #7—Construction Process: The effective construction of systems (e.g., envelope and mechanical systems) facilitated by knowledgeable construction teams in green construction under strict field control is important to better performing HPG buildings.

Control Variables: There are variables in the project delivery process that project teams should control for, such as project characteristics and external environment. These variables lead to differences in performance outcomes even when all of the other project delivery process-related variables are kept constant.

EO # 2—Process Indicators: Exemplary projects exhibit a larger number of process indicators. Exemplary projects in this research were as defined as the projects that reach high levels of energy and indoor air quality performance within project budget limits.

EO # 3—Data Collection Tool: Online data collection tool applications, that can grant access to different project participants for a single project, are effective in collecting project delivery data for defining reliable evaluation metrics for HPG building project delivery.

3.3.5 Data Collection Procedures

After the data collection tool was developed, tested, and verified, the research study proceeded to the next step: to perform data collection on identified building projects. Based on the lessons learned from the pre-study and review of existing databases, strategies were developed for the data collection phase. The data collection tool development phase was finalized after the review and approval of the survey by the

Institutional Review Board (IRB) at Penn State for compliance with human participant research rules. Target projects were limited to green office buildings to control variability in the data set due to the presence of different facility types. The selected projects were not limited to any specific population. Geography, organization, and project team variety in the target population was a priority for overcoming sampling error and producing results that can be generalized to the entire HPG building projects population. A web-based survey system was utilized to collect data. Chapter 5 presents study population characteristics, procedures used to collect data, study response rate, steps followed to record and standardize the collected data, and tactics followed to increase data quality.

3.3.6 Data Analysis Methods and Results

Upon completion of the data collection, the researcher analyzed the data to meet the following objective: Examine the collected data using mixed methods to identify HPG building project delivery evaluation metrics. Data analysis began with a quantitative analysis approach to select the meaningful evaluation metrics needed to define HPG building project delivery through statistical examination of the collected project data. The data analysis then was followed by the qualitative approach to support the findings of the quantitative analysis, and to learn additional lessons from case study analyses and exemplary projects.

Quantitative Data Analysis and Results

In the quantitative analyses the researcher examined the associations between project delivery process attributes (e.g., project delivery system selection, contract conditions, procurement methods, timing of project participants' involvement, and team characteristics) and performance outcomes in terms of cost, time, quality, safety, and levels of high performance in HPG building projects. The study mainly included seven process indicators and five performance metrics. As described in Chapter 4 in detail, several variables were identified under each of these evaluation metrics to understand HPG project delivery. With the addition of control variables, the number of variables examined in this research exceeded one hundred.

Deciding on the scale of measurement for the variables is important in identifying the type of analysis method to be used in statistical analysis. Here, the research variables were categorized according to their types of scales (e.g., categorical and continuous). The statistical analyses were conducted in two main steps: univariate and multivariate. Minitab® statistical software was used to perform data analysis.

First, the study utilized univariate analyses to see if a relation existed between each independent variable (that defined a process indicator) and each dependent variable (that defined a performance metric). One-way ANOVA (analysis of variance) was used to ascertain whether means-dependent variable values differed according to the levels of categorical independent variables. Regression analysis was also utilized to detect associations between dependent and continuous independent variables at this stage. Significant relationships (p value< 0.05) and relationships with the potential to become significant with larger sample sizes (p value < 0.2) were recorded. Findings from the univariate analyses helped to identify relation patterns between the process indicators and performance metrics and screen the meaningful evaluation metrics to be used at the multivariate analysis stage and in future research efforts.

The next step in the quantitative data analysis was the multivariate analysis, in which all significant independent variables selected in the univariate analysis stage as well as the control variables were included in the analysis for one dependent variable. Multivariate analysis is reliable in producing results since it considers the effects of all variables on the dependent variable, eliminates the redundant variables, and/or combines the variables with same effects. The literature recommends the use of analysis of covariance (ANCOVA) when the study involves mixed types of data (continuous and categorical) for independent variables, and continuous data for dependent variables (Cho, 1997). Therefore, ANCOVA was used in this study for the multivariate data analysis.

The extensive number of variables to be investigated, numerous levels associated with some of the independent and control variables, and limited sample size of the study hindered the abilities of the statistical analyses at this stage. Although several project delivery attributes were found to be significant at the multivariate analysis stage, the results of the quantitative analysis were limited due to the presented challenges associated with the research characteristics.

Chapter 6 presents the steps followed in conducting the quantitative analysis and the results of the statistical analyses. In that chapter, the researcher also explains the limitations of this study and presents a power analysis to reveal the sample size needed in future research studies to detect the desired differences at given significance levels.

Qualitative Data Analysis and Results

The mixed-method data analysis was continued in the qualitative analysis to support the findings of the quantitative analysis, explain various quantitative analysis results thorough the case study approach, and define additional project delivery metrics through qualitative data collection and analyses methods. Yin (2002) defined a case study as:

> "…an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident."

This research specifically utilized the case study approach due to the limited number of exemplary projects within the sample of the study as well as in the population, since the green market is still at its infancy. The case study tactics employed within the qualitative research design to satisfy the research quality criteria are summarized in Table 3-2.

Table 3-2: Case Study Tactics for Four Design Tests (Yin, 2002)

Tests	**Case Study Tactic**	**Phase of research in which tactic occurs**
Construct Validity	* Use multiple sources of evidence	Data Collection
	* Establish chain of evidence	Data Collection
Internal Validity	* Do pattern-matching	Data Analysis
	* Do explanation-building	Data Analysis
	* Address rival explanations	Data Analysis
	* Use logic models	Data Analysis
External Validity	* Use theory in single case studies	Research Design
	* Use replication logic in multiple case studies	Research Design
Reliability	* Use case study protocol	Data Collection
	* Develop case study database	Data Collection

- Constructing validity is necessary to create correct operational measures;
- Internal validity is important in explanatory studies to establish casual relations;
- External validity presents the field that the study findings can be generalized; and
- Reliability represents the operations of a study and important for the repetition of similar studies (Yin, 2002).

The following tactics were employed in this study to satisfy the research design quality criteria: multiple sources of evidence to construct validity, pattern matching for the study's internal validity, theoretical replication logic for the study's external validity, and a case study database for the study's reliability.

Chapter 7 contains an explanation of data collection techniques adopted for the qualitative data analysis, the methods used to conduct case study data evidence analysis, strategies to link for linking the data to the results, and the criteria used to interpret the findings. The study used pattern matching among similar projects and cross-case synthesis across good/bad projects as the case study analysis procedure to analyze the evidence in the case studies. Results from the qualitative analysis triangulate the findings from the quantitative analysis phase and also capture additional useful evaluation metrics for HPG project delivery. Chapter 7 expands the lessons learned from case studies by presenting the highlights of exemplary projects and respondent quotes on HPG building project delivery.

3.3.7 Summary of the Research Findings

The data analysis was followed by a summary and discussion of the findings in Chapter 8 to meet the objective of refining the results, summarizing research contributions, and making recommendations for future research. The last chapter also contains a discussion of how research findings relate to the expected outcomes and the limitations of the research.

3.4 Research Limitations

While the HPG building market is emerging, there are a limited number of completed and certified green or high-performance projects in the industry. This leads to a small population and a potentially small sample size for field studies. The strategy to limit the target population to green office buildings in order to control data variability created an even smaller population. Therefore, the results may not be generalized to the entire green building project population. The results generate a reliable foundation for future HPG building project delivery research. As more green building data are gathered and more exemplary projects emerge, the results can be more significant and representative of the industry.

On the other hand, as new technologies for applying high-performance green features and the construction community’s knowledge of green buildings progress, the way in which the green construction industry delivers HPG building projects will evolve. The results from this study are limited to knowledge and applications available in the current industry. HPG building project delivery research should be continued to capture innovative practices in project delivery that will maximize HPG project performance outcomes in the future. Limitations of the analysis procedure, research sample, and results are explained in further detail in Chapter 8.

3.5 Summary

This chapter contains a description of the methods and process followed in this research study. A mixed-method strategy that utilized quantitative and qualitative approaches was used as the data analysis method. A web-based survey format was selected as the primary data collection tool to primarily increase the survey response rate. Data collection tool design and application procedures were briefly described in this chapter. The survey application was followed by interviews, review of archival records and documentations for the case study approach. The tactics used here to satisfy the validity and reliability of the research were also described.

As a result of this exploratory research, which involved a mixed-method strategy for data analysis, evaluation metrics for defining HPG building project delivery, a data collection tool and methods for the feasible collection of meaningful HPG building project delivery data, and data analysis methods for HPG building project delivery research were developed. The details of the data collection tool development, data collection process, qualitative and quantitative data analysis procedures, and results are presented in subsequent chapters.

Chapter 4

Data Collection Tool Development

The research objective to examine the relations between the project delivery attributes and project performance outcomes in high-performance green (HPG) buildings directed this study to create a tool for data collection to be applied on green building projects. The project delivery attributes and performance outcomes of green building projects have similar characteristics in terms of the parties to provide data regarding these variables. Therefore, this research employed a single data collection tool: a survey. This chapter first presents a description of the evaluation metrics used in this research to understand HPG building project delivery. The chapter then gives the steps followed to develop, verify, and finalize a survey design for collecting data based on the developed evaluation metrics for this research.

4.1 Evaluation Metrics for HPG Building Project Delivery

The literature review helped this research to identify a preliminary set of metrics to evaluate HPG building projects at their project delivery/pre-occupancy stage. These metrics are reviewed under two major categories: project delivery attributes and project performance upon the completion of construction. The project delivery evaluation metrics can also be classified as follows, to identify their level of contribution to evaluation:

1) **Independent variables**: Project delivery process indicators (PIs) that can influence project performance and which owners and/or project teams can have control over;

2) **Control variables**: The characteristics of projects or those which exist within project environments that can affect project performance even if all the independent variables were kept constant; and

3) **Dependent variables**: Project performance metrics (PMs) that measure the project outcomes and are affected by independent and control variables.

Figure 4-1 is an illustration of the evaluation elements for the project delivery/pre-occupancy phase. This section explains these elements in detail.

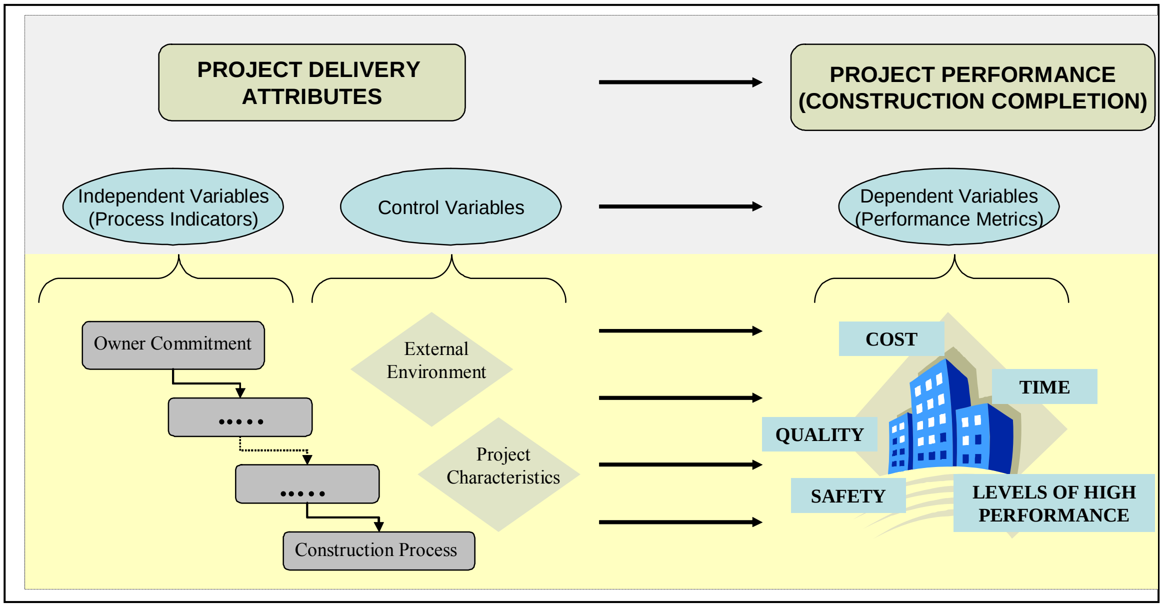


Figure 4-1**:** Project Delivery/Pre-Occupancy Phase Evaluation Elements

4.1.1 Independent Variables: Process Indicators

Process indicators (PIs), defined as independent variables in the project delivery evaluation, are the main focus of this research. The literature review helped to identify seven process indicators (PIs) for the project delivery of HPG buildings. These are as follows: owner's commitment, project delivery system selection, project team procurement, contract conditions, level of integration in the design process, project team characteristics, and construction process. These PIs are explained in further detail below.

PI # 1 – Owner Commitment: It is observed in the literature that the type of owners (e.g., public, private, developer) and occupants of buildings are driving forces of an owner's commitment to pursuing sustainability. Owners tend to invest in the high-performance features of projects in cases where they are also the occupants of the buildings, in order to enable low life-cycle cost and improved productivity of employees.

High-performance features are harder to add on to the building projects as a design proceeds. The combination of earlier decisions and a project team that is motivated to build high-performance green buildings generates a better chance of achieving high-performance green goals in a project. An owner is the most important actor in a project team, since he sets the priorities for a building project. Therefore the owner's commitment to HPG features can be the driving force for the achievement of the HPG goals at the end of the project delivery process. PI#1 explains the level of an owner's commitment to high-performance green features of a building project by evaluating criteria such as the party to introduce "green" features to the project, the reason to pursue "green" objectives, the timing of introducing the "green" concept in the process, and the importance of the "green" goals for the project.

PI # 2 – Project Delivery System Selection: Project delivery systems define major project participants' official involvement in the project, the level of integration, and contractual relationships between project parties. Project delivery system selection can influence the HPG project performance outcomes. Three types of project delivery systems are widely used in the USA: design-bid-build, design-build, and construction management at risk.

PI # 3 – Project Team Procurement: Success in the construction industry is very dependent on the individuals working at key positions in a given project. Therefore, project teams' selection is an important component of the delivery process in order to achieve the set goals of a building project. The use of diverse criteria in the project team selection process, such as past experience of a project team and technical aspects of a proposal may, contribute to HPG project performance outcomes. The way major project parties as well as primary subcontractors (e.g., mechanical and electrical contractors) are selected also play an important role in the overall success of HPG building projects.

PI # 3 determines how the project teams were procured based on criteria that include the method and process of procurement and the criteria spelled out in the request for proposal for the selection of the major team members.

PI # 4 – Contract Conditions: Project teams are more likely to achieve their HPG goals when these goals are tied to incentives and/or penalties in the projects' design and construction contracts. Moreover, the contractual terms used for the design and construction contracts are likely to affect project performance outcomes such as cost growth. Commonly used contractual terms are lump sum, guaranteed maximum price, and cost plus fee. Lastly, holding contracts with key team members that play critical role in achieving HPG goals is likely to increase an owner's control over important decisions. These key members include green design facilitator, energy and lighting consultants, and mechanical/electrical subcontractors.

In summary, PI # 4 defines contract conditions within a HPG building project by evaluating contractual terms of the project, the importance of "green" in the contract, contractual relations between important team members, and incentive/penalty clauses within the contract.

PI # 5 – Integration in the Design Process: High interaction between project actors and improved communication in the design process are likely to contribute to achieving HPG goals. Even though the project delivery systems are believed to define the level of integration in the design process, further investigation of additional elements is needed to understand PI # 5. These elements include the timing of project participants' involvement in the project delivery process and the level of interaction between team members for achievement of high-performance green goals. For example; earlier involvement of key project participants (e.g., contractor, energy and lighting consultants, commissioning agent) in the HPG project delivery process is likely to lead to better project performance outcomes.

PI # 6 – Project Team Characteristics: Project teams competencies such as previous experience with similar facilities, the project delivery system, and high-performance green buildings, along with improved communication between team members, contribute positively to the success of HPG building projects. Therefore, PI # 6 uses evaluation of project team members’ experience, team communication and chemistry, and owner’s capabilities to understand the project team competencies.

PI # 7 – Construction Process: Effective construction of systems is related to subcontractors’ knowledge and experience with HPG features. Application and quality control procedures regarding the envelope and mechanical systems of buildings are particularly important for the achievement of HPG goals, therefore are considered in defining the PI # 7.

Overview

The presented process indicators may not only affect performance outcomes, but also can also influence each other. For example; project delivery system selection and contractual relations would not completely describe but would affect the level of integration at the design process. As another example; the primary reason to build high-performance green buildings might influence contractual relations between key project participants. An owner whose primary intention to only receive a green certification is likely to hire a green design coordinator and have a direct control over certification process; where as an owner that desires a HPG building might decide to hold a direct contract with mechanical and electrical subcontractors.

The defined PIs and the interactions between them can be critical in the HPG building project delivery to enable better project performance outcomes. However, there are also other important variables in project delivery processes of HPG buildings to influence project performance outcomes. These variables are classified under control variables in this research.

4.1.2 Control Variables: External Environment and Project Characteristics

Control variables in the HPG building project delivery differ from the independent variables with their relation to the project environment and project characteristics. One of these variables is “the external environment” that defines the existence of qualified contractors, regulations, and a building industry's client profile in the projects' geographical locations. These are the variables that an owner does not have control over. However, they can have positive or negative effects on the performance outcomes. Other control variables are related to the project characteristics including project size, complexity, and the type of systems used in the buildings.

For example, some structural or mechanical systems might be difficult to apply or procure, therefore can lead to cost or schedule growth. On the other hand, certain mechanical systems might be highly efficient to create better energy performance levels, while they come with a high first cost.

Another example about the control variables is the effect of the location on the project outcomes. Location can be a driving factor when it comes to cost and schedule performance of a building, considering its proximity to suppliers and contractors. It is also observed in the literature that location influences the level of HPG features employed by building projects. For example, the driver for a green market in the Washington, D.C. area may be part of a governmental institution. The federal government either permits higher building intensity ratios for green buildings or occupies only green buildings. Either way, the government motivates the construction community to build "green" around the Washington, D.C. area. However, as observed in the pre-study conducted for the survey verification of this study, most of the time the measure to build "green" is only receiving LEED™ certification for the buildings. Therefore, buildings in this area hardly go beyond low certification levels and become high-performance green. Conversely, in states such as California, high-performance levels are more likely to be reached, in those areas where local energy codes are very stringent (Kats, 2003). Overall, external environment and project characteristics are variables that need to be controlled in the HPG project delivery since they can contribute to the generation of better or worse project performance outcomes.

4.1.3 Dependent Variables: Performance Metrics

Dependent variables in HPG project delivery are the project performance metrics (PMs) to measure HPG project performance and are used to understand the effects of project delivery attributes (independent and control variables) on the project outcomes. Cost, time, quality, and safety are widely accepted performance metrics to measure project outcomes. Levels of HPG achievement is an additional metric for HPG projects to understand how the projects perform in sustainability, energy and indoor environmental quality aspects. There are five PMs identified within this study:

PM# 1 – Time: Time is an important metric for building construction project success for several reasons. Owners generally have tight schedules for moving in the buildings and/or opening the buildings for occupancy; construction budgets can be affected by material cost escalations if the projects go over time, and schedule growth increase general conditions for construction projects, in other words time equals cost in construction projects. Delivery speed, construction speed, and schedule growth are potential measures to evaluate HPG project performance and are based on the definitions provided by Konchar and Sanvido (1998) in this research.

The first metric for measuring project time performance is construction speed, and can be measured by dividing the total project area by project delivery time. This metric is calculated as follows:

Construction Speed (SF/Month) = [(Area / Actual Construction Time in Days)/30]

Schedule growth is the second metric used in this research to measure project delivery process's time performance. Schedule growth represents the difference between total planned project delivery time and total actual delivery time where project delivery time is defined as the time that starts with the project design start and ends with the construction's completion in this research. This metric is defined by the formula below:

Schedule Growth (%) = [(Total Actual Delivery Time-Total as Planned Time) / Total as Planned Time] 100*

The last metric to measure project time performance is the delivery speed which is defined by the rate of the building size to the total project delivery time.

Delivery Speed (SF/Month) = [Area / (Total Actual Delivery Time in Days / 30)]

PM# 2 – Cost: Cost defines the magnitude of the investment made by a facility owner or a developer to design and construct a building and excludes property costs, owner costs of installed process or manufacturing equipment, furnishings, fittings and equipment, or items not included in the cost of the building. Three metrics, which are adopted from Konchar and Sanvido (1998) are used within this study: cost growth, unit cost, and intensity.

The first PM used for cost in this research is the cost growth that measures the growth of the project costs in the project delivery process as a percentage. This metric can be formulized as follows:

Cost Growth (%) = [(Final Project Cost-Contract Project Cost) / Contract Project Cost] 100*

The second cost PM is the unit cost where the relative cost of a building is calculated for its given size. A cost index was used in this metric using Means 2006 historical cost index, in order to be able to make appropriate comparisons between projects that were built in different years and locations. Unit cost in this research is calculated as follows:

Unit Cost ($/SF) = (Final project Cost / Area)/Building Cost Index

Intensity is the last metric used in this research for cost. It measures the work put in place in a project delivery process per unit time by combining project unit cost with total project delivery time. The metric is calculated as follows:

Intensity [($/SF)/Month] = Unit cost / Total Time

PM# 3 – Quality: Quality of a project is relative and can differ for different team members. In this research, quality is defined as the owner’s level of satisfaction with the project characteristics. The quality metric includes turnover quality, system quality, overall quality, and value of project cost for the project owner. The first two metrics presented here are adopted from Konchar and Sanvido (1998).

The first quality metric, *turnover quality*, measures the difficulty of the facility turnover to the owner. This metric combines the difficulty of facility start up (Qstartup), number and magnitude of call backs during the turnover process (Qcall backs), and the difficulty of the submittal review process if the facility went through a documentation submission process for receiving certification from any of the environmental building assessment systems (Qsubmittal review). Each category in this metric is evaluated by the respondents in a Likert scale, ranging from 1 to 5, where 1 represents high, 3 represents medium, and 5 represents low difficulty in these processes. A total of 15 points are possible in the evaluation of this metric. Turnover quality of the facility is considered as a separate metric in this study since it can affect owners' perception of project quality in cases where the turnover of the facility has been difficult. The formula to calculate facility turnover quality is as follows:

$$Turnover\ Quality = Qstartup + Qcall\ backs + Qsubmittal\ review$$

The second quality metric, *system quality*, combines the quality of the envelope, roof, structure, and foundation; the quality of the interior space and layout; and the quality of the environmental systems such as lighting and HVAC. Similar to the previous metric, a Likert scale from 1 to 5 is used to measure if the facilities' system quality in each category meets the owner's expectation, where 1 represents that it did not meet expectations at all, 3 represents that it met expectations, and 5 represents excellent success regarding the expectations. 15 points in total are possible in this category, where high scores represent higher levels of owner satisfaction as well as higher quality. The metric is formulized as follows:

$$System\ Quality = Qerfs + Qis\ \&lo + Qen$$

The third quality metric, overall project quality is a relative metric and represents the level of project team satisfaction with the project outcomes. This metric combines project success from a project team's and owner's perspective, with the condition of meeting the intended project and HPG goals. This metric uses a Likert scale from 1(poor/did not meet expectations) to 5 (excellent/exceeded expectations) respectively and is calculated with the formula given below. A total of 20 points is possible for each project in this metric, where high points indicate higher levels of project success.

$$\textit{Overall Quality} = Sprojectteam + Sowner + Sgoals + Shpggoals$$

The last quality metric in this study is related to an owner’s satisfaction with the cost of the facility. Cost growth during the delivery of a facility may result from owner-related scope changes or an owner might be satisfied with the end result despite the high unit cost. Therefore, it is important to measure an owner’s satisfaction with the cost performance of the building, even though the research includes cost metrics as another category to measure project performance. The Likert scale used in measuring system quality is also used in this metrics.

PM# 4 – Construction Safety: There are controversial thoughts regarding construction safety in HPG buildings. Several HPG strategies that lead to indoor environmental quality improvement such as the use of low emitting materials can contribute to the well-being of construction workers. Moreover, integrated design approaches and strategies can make buildings easier to build and equally safe. Conversely, complexity of design in HPG buildings, and recycling requirements for materials such as steel, can degrade the level of safety in these projects. Therefore, safety is an important metric to consider in the evaluation of HPG project performance outcomes.

Safety can be measured by Occupational Safety and Health Administration (OSHA) recordable incident ratings on the projects. The following metrics are used to measure constructions’ safety levels in this research: (1) OSHA Recordable Incident Rate (RIR); (2) DART Rate (Days Away/Restricted or Job Transfer Rate); (3) Lost Time Case Rate (LTC); (4) Lost Work Day Rate (LWD).

PM# 5 – Levels of High-performance Green: Using a reliable method to measure projects’ levels of HPG is an essential part of this research. This study focuses on the project performance at the end of the project delivery process, based on the assumption that practices and design strategies implemented during the design and construction processes of the building projects lead to high-performance levels. For example; the existence of envelope systems that comply with or perform better than ASHRAE’s requirements in a building is an indicator for less energy consumption, or for the use of low VOC emitting materials in the buildings, which help to create better indoor environmental quality. Environmental building assessment systems such as LEED^{TM} and Green Globes^{TM} apply a set of consensus based criteria to certify the buildings in the U.S based on the practices and strategies implemented during the design and construction phases of buildings. These criteria include sections for indoor air quality and energy aspects and are found to be useful to understand the levels of high-performance in green buildings. For example, higher level (e.g., gold and platinum) LEED^{TM} certified green buildings are identified to be better performing in energy and indoor air quality aspects (Katz et al., 2003). Therefore, existing building environmental assessment tools were examined to adopt methods of measuring building HPG levels.

There is a consensus among the existing building assessment systems on the critical elements of design and construction to enable high-performance buildings. Among these systems, LEED^{TM} (USGBC, 2006) has received the greatest recognition in the US green building community. Therefore, the LEED^{TM} criteria to assess energy and indoor environmental quality (IEQ) were adopted in the survey to measure high-performance levels of green projects. This decision also facilitates easier data collection for this research since LEED^{TM} certified buildings constitute a large focus group for this study. Criteria to be used by non- LEED^{TM} projects were also written to facilitate accurate comparisons between projects.

The examination of the LEED^{TM} energy and IEQ sections show that some of the criteria in these sections might conflict with each other. As an example, the criteria to maximize the daylight use in buildings under IEQ section calls for the use of more fenestration in the buildings. However, openings in the envelope might jeopardize the energy performance of the building and would conversely affect points achieved in the energy section of LEED^{TM}. The relations between energy and IEQ are important in this research to formulize the performance metrics. Therefore, a regression analysis was conducted to investigate their relations. The results show a positive relationship between the energy and IEQ points achieved in LEED^{TM}. However, only 13.4% of the variance in energy points was related to the IEQ points. Therefore, these sections are determined to be considered as different metrics. The metrics used to measure levels of HPG in project are calculated as follows:

Energy Performance = (Achieved Energy Points in LEED^{TM} _/ Total Possible Points in Energy Section)*100_

Indoor Environment Quality Performance = (Achieved IEQ points in LEED^{TM} _/ Total Possible Points in IEQ Section)*100_

Level of Green = (Achieved Total Points in LEED^{TM} _/ Total Possible Points in LEED_^{TM} _)*100_

4.2 Preliminary Survey Design

After the evaluation metrics for HPG building project delivery were defined, the study proceeded to the next stage: designing a survey to collect data on the defined metrics. The research propositions presented earlier in Chapter 3 have the same characteristics: each of them proposes that a project delivery process indicator (PI) or a control variable correlates to project performance metrics (PMs) in HPG building projects. All of these propositions are measurable through the application of a survey on HPG building projects. Few of the HPG project delivery research components are latent variables that can not be measured directly. Therefore, a survey is designed to collect data on these latent variables as well as the measured variables for the HPG building project research. The Figure 4-2 below presents an illustration of the survey.

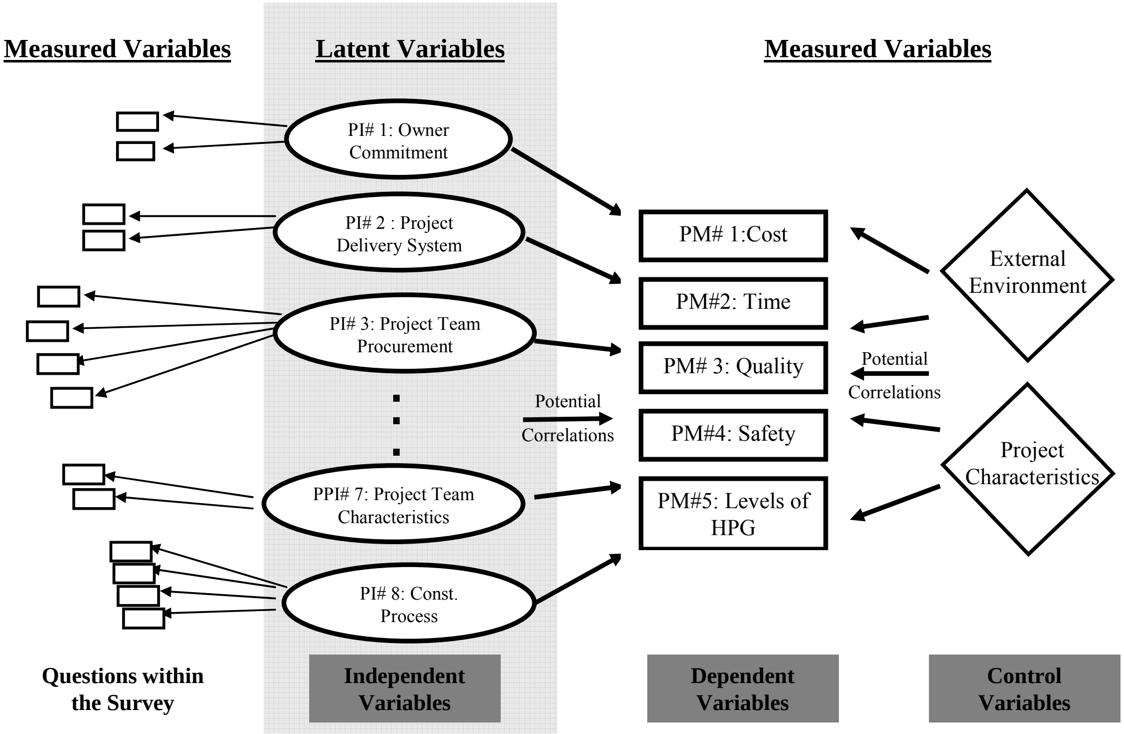


Figure 4-2**:** Representation of the designed survey to collect data on HPG project delivery components

Mainly based on the prior studies conducted at Penn State (Konchar and Sanvido, 1998); El Wardani et al., 2006) a set of questions was formed as a part of a preliminary survey design for this research. A table that summarizes the questions within the design of the survey, according to the developed proposition, is presented in the Appendix B.

4.3 Survey Verification

The preliminary survey design phase was followed by the survey verification phase. The verification of the study included receiving industry professionals' feedback: The first round of the survey verification was executed at the Partnership for Achieving Construction Excellence (PACE) Roundtable at Penn State in 2005. The second round of the verification was completed in Washington D.C. where industry professionals that worked on green buildings were asked for their opinions on the clarity and the competency of the survey questions in measuring project delivery attributes for HPG building projects. The industry professionals included owners, developers, architects, project managers working for contractors, green design professionals/ LEED^{TM} accredited consultants, and mechanical engineers/consultants.

Improvements were made to the survey after each verification phase. Addition of new process indicators in the project delivery evaluation metrics as well as in the survey in the form of new questions was a significant result of the survey verification phase. Contractual relations and construction application procedures were among the process indicators that were included in the study as a result of the survey verification phase. Lessons learned in this phase also helped to develop strategies on survey application which will be described in detail within the next chapter.

The verification phase resulted with a final survey that includes 38 close-ended project delivery process and performance related questions. The final survey can be seen in the Appendix B. The questions within the final survey are a mixture of Likert scale, categorical, and numerical types. A set of open-ended questions are also presented at the end of the survey about lessons learned in the projects, to enable descriptive conclusions for the study. After the data collection tool design was finalized, the study proceeded to the next stage: the data collection process.

4.4 Summary

This chapter described the primary set of evaluation metrics defined for HPG building project delivery. These evaluation metrics include: independent variables (process indicators) and control variables under project delivery attributes; and dependent variables (performance metrics) to evaluate project outcomes. Followed by the explanation of the HPG building project delivery evaluation metrics, the preliminary survey design process and survey verification steps were described in this chapter. The study is continued with the data collection procedure explanation in the next chapter.

Chapter 5

Data Collection Procedure

This chapter presents study population characteristics, data collection procedure, study response rate, data verification methods, and procedures with which to record, categorize, adjust, and standardize the data. The chapter also explains the tactics used to satisfy the data quality and presents the quantitative and qualitative methods to analyze the data.

5.1 Study Population Characteristics

The challenges based on the research characteristics in this field and the limitations in the market were presented earlier in Chapter 3. Based on the presented reasons, it is necessary to limit the types of buildings with which to collect data from in this research, in order to reduce the variability in the data set and increase the power of the data analyses. Office buildings are the type of buildings that owners are mostly motivated to employ HPG features on, due to reduced building life-cycle costs and improved occupant productivity HPG buildings provide. Therefore, the target population for this research was limited to green office buildings.

It is also important for this research to understand the features that make a building high-performance green to collect the right project. Therefore, the sample for this study was limited to green projects in the U.S., those included in the green database systems reviewed in Chapter 2, and the LEED^{TM} criteria for energy and indoor air quality was followed to detect levels of high-performance in the green office building projects both from both the public and private sectors.

5.2 Data Collection Steps

This section describes the process to gain institutional review board approval for this research and explains the survey implementation process and data collection procedures followed in this study.

5.2.1 Institutional Review Board Approval

After the data collection tool design was finalized, the final version of the survey and the data collection procedures were reviewed and approved by the Institutional Review Board (IRB) at Penn State, for its compliance with the rules of human participant research. An implied informed consent form was created to be used to inform the respondents about the research goal, objectives, survey application method, the time it takes to fill the survey out, its storage, and the use of collected data. This form, which can be seen in Appendix C, was distributed to the respondents of the survey before they began the survey.

5.2.2 Survey Implementation

The respondents to the survey were project managers that have overseen the design and the construction processes of green office building projects. The survey included different types of questions about project delivery processes, building systems specifics, and quality evaluations. Therefore, the survey implementation required including different project participants such as designers, contractors, owners and mechanical/electrical system engineers. These participants were identified through web-based research.

Project managers that have worked on the identified projects for owners, designers, and/or contractors were invited to participate in this research through phone calls and/or e-mails by the primary investigator. The invitations informed the participants about the goal of the study, the research methods, the timeline for the research, and the approximate time they need to devote to participating in this research. Additionally, a research flyer was used to recruit participants. This research flyer was handed out in the conferences that interest the green construction community, and was also displayed on the website of the Lean and Green Research Initiative at Penn State (www.leanandgreen.org). The designed flyer for participant recruitment can be viewed in the Appendix D.

Once the project managers of the selected buildings responded with interests, the primary investigator e-mailed a link to the participants for taking the online survey. After respondents accessed the web page, they then accessed the informed consent form and were directed to start the survey as they agreed to proceed. A commercial web-based package, *SurveyMonkey*, was utilized for survey application in this research.

The main advantage to using a web-based format for survey application in this research is two-fold: 1) A variety of locations in which to perform the data collection; and 2) The potential of web-based surveys to reduce the non-response rate. Web-based surveys eliminate delays in postage and enables instant access to respondents. Moreover, the interactive format of web-based surveys motivates respondents and reduces the non-response rate.

5.2.3 Data Collection and Follow-up

A follow-up study was conducted with the respondents after the preliminary data collection in order to increase the response rate within the collected surveys. Follow-up study included identifying different project participants, conducting phone interviews with them, and/or sending them customized online surveys with the non-response sections. The need to involve different project parties into the data collection process to receive the answers of different questions lead the researcher to break the survey into sections according to the type of project participants who can answer those questions and send them separately to related respondents to increase response rate.

5.2.4 Problems Encountered in the Data Collection Process

The researcher observed several drawbacks during the data collection process that decreased the response rate and caused non-responded questions within the surveys:

- Lack of a publicly accessible database in the green construction community other than case study based websites, that presents the contact information for green building project participants;
- High turnover rate in the construction industry and the difficulty to reach the individuals that have worked on focus projects;
- The difficulty respondents experience in finding the data needed to complete this survey due to lack of database systems in construction companies to store the project specifics for easy access after the projects are completed;
- Lack of knowledge to answer each question in the survey due to the need of a large knowledge base spanning from planning and design to construction process and systems characteristics for filling out the survey;
- Lack of motivation and time to fill out the survey;
- The variety of the project participants needed to answer the survey questions. (Typically, one participant can not respond to all of the questions due to lack of knowledge or not being involved in the project at all phases); and
- Confidentiality concerns about some of types of data, such as design and construction costs, results in unwillingness to share them even for research purposes.

5.3 Study Response Rate

The green office building projects database developed for this research included 209 projects. The response rate was 30% after the initial data collection phase. However, 21 of these projects did not meet the research criteria. Moreover, the submitted surveys had a large number of non-response questions. The response rate within the submitted surveys was increased by the follow-up phase with the respondents and included different project parties for every single survey, adding to the data collection process. The final data set includes 40 green building projects.

5.4 Data Verification

The primary verification was conducted on determining if the project met the research criteria based on the facility and construction type. Many LEED-NC (new construction) certified green building projects that were primarily included in the target projects list were excluded from the data set due to their focus on interior finishes.

Data was collected primarily based on the web based system. However, follow-up study for non-response data was performed via e-mail and phone interviews. Data collection process also included 7 face-to-face interviews. Due to the use of various data collection methods, the verification of the collected data became essential. Survey data was verified through cross referencing different project participants' answers for the same project. The uncertain data was filled out after follow ups and phone interviews with the respondents. The data was also checked during the statistical analysis stage to detect any outlier data points. Other sources of green building data were also utilized to verify the collected survey data, such as online case study resources and green building publications that includes case study specifics. Special focus was placed on inconsistent data where related answers did not confirm each other, such as the sum of the design and construction costs not equaling the final cost.

5.5 Data Recording and Categorization

Several spreadsheets were used to store target project and respondent information. The spreadsheets were updated as project participants were contacted. These spreadsheets included project information such as the source the project was initially found at, facility type, project location, project participants' roles and contact information including e-mails, companies and telephone numbers. The researcher used these spreadsheets to contact respondents and keep track of contact status. After the respondents filled out the online survey, the responses stored at the online repository were extracted to a spreadsheet. Non-response data was than filled out on these spreadsheets as the respondents were 'followed-up' via phone calls or e-mails.

The collected data was firstly recorded in the spreadsheets numerically in the order they appeared in the survey. The coding was then changed as the categories were combined under each section, based on the exploratory data analysis where necessary. The questions were categorized in the spreadsheets based on the developed research propositions for the ease of data analysis. The data was exported to Minitab®, which is a statistical software package, after the coding was completed.

5.6 Data Adjustments and Standardization

The designed survey applied several techniques to assure the quality of the data collected. The LEED criteria were adopted to measure the project levels of high-performance green. Two concerns have risen due to use of these criteria. The first one was related to inclusion of non-LEED projects in the study. Two sections regarding the energy and indoor environmental quality performance were added to the data collection tool to understand those projects' performance. Additional case study information was gathered from the respondents of these projects to understand the green performance of these projects. The second concern was regarding the use of different versions of LEED-NC by various projects. Even though there were slight changes between LEED-NC versions, the researcher avoided the use of a point system in the data recording to avoid error in the coding. Instead, a rate of achieved points out of possible points in LEED^{TM} was used for the proper adjustment.

Cost adjustment was also essential, since the collected projects were built in different locations in the US in different years. RS Means historical construction cost database 2006 was used as a reference to identify a cost index for each project. Adjustments according to the years and locations were realized for reliable comparisons of cost data in the analyses. It is important to note that, the cost data was not normalized based on other control variables such as building systems' employed within the projects, and the site and weather conditions specific to the projects. This is a result of the difficulty on gathering such data from construction projects, especially related to the confidentiality concerns of respondents regarding the cost data. As a result, the cost data within this research is not adjusted for all control variables, and therefore can not be evaluated as precise cost comparisons in the analyses. The limitations regarding this metric and recommendations for future research are presented in Chapter 8.

5.7 Data Quality

This research employed several tactics to satisfy the research quality criteria. These tactics addressed sampling error, response bias and non-response and are explained in detail below.

5.7.1 Sampling Error

Geographical region, owner, project team, and project delivery system variety in data sets are important factors to regard when attempting to eliminate the sampling error in data sets. Geographical diversity is necessary to capture different high-performance levels and process characteristics. As it is observed in the literature, the federal government in the DC area promotes LEED certification through permissions for higher construction intensity or requirements in lease contracts. However, “LEED certification achievement” focused delivery processes do not lead to high levels of performance. On the other hand, the literature review also shows that stringent local energy requirements in California help develop highly performing buildings (Kats et al., 2003). Therefore, it was important to obtain geographical region variety in the sample.

Moreover, the projects owned and/or delivered by the same organizations were limited to eliminate the risk of producing biased results. Lastly, the literature defines that the project delivery methods are essential in explaining the project delivery characteristics. Therefore, having a mix of projects built under different project delivery methods is essential for the results of the project to be unbiased. Overall, the selected projects were not limited to any specific population. Geography, organization, project team and project delivery system variety in the target population was a priority in this study to overcome sampling error and produce results that can be generalized to the whole HPG building projects population.

5.7.2 Response Bias

Another important issue in data quality is related to the team characteristics section of the survey. Experience and performance of team members differ according to different team members’ perception. To eliminate the response bias, all project participants for each project (the owner, designer, and contractor) were included in the data collection process for the team characteristics evaluation questions. The responses were coded and their average generated the final response for these questions.

Similarly, evaluation on facility complexity was based on respondents’ perception. In some cases, answers for the same facility differed according to the project participants’ level of experience in the industry and with the facility type. Therefore, the researcher controlled the answers on facility complexity by cross checking those with the experience of the respondents’ experience in the field.

5.7.3 Non-Response Bias

Literature shows that field studies in the construction industry lead to a high non-response rate (Konchar and Sanvido, 1998; El Wardani et al., 2006). This study also resulted with a large non-response rate after the initial data collection process. Most of the respondents were contacted again, and/or 'followed-up' to reduce the non-response rate after the initial round of data collection phase.

Some of the respondents were unwilling to participate in this research since their projects were on the low end of the high-performance green scale. However, these projects' inclusion to the study sample was essential to avoid a bias towards good performing projects in the study sample. The data collection tool of this research focuses on projects and asks objective, project related questions that does not take respondents' point of view into account with the exception of quality and team characteristics questions. Therefore, the unwilling respondents' involvement in the research was not essential for avoiding non-response bias in this study, but inclusion of projects with lower high-performance green levels was crucial. To minimize non-response bias in the study sample through data collection procedures, the researcher contacted various project participants for non-response projects to ensure their inclusion in the study sample, especially if they are considered to have low HPG levels.

It is important to perform a non-response analysis to ensure that the study sample is representative of the entire population and the results can be generalized. Due to the limited number of available projects for this study, a data analysis to make comparisons between the non-response data set and the original data set was not performed. On the other hand, an advantage of this study is that the performance outcomes data of the study sample were normally distributed. In other words, a bias towards any of the performance levels (e.g., projects with higher green rates) was not observed in the study sample. Therefore, the study sample is representative of the U.S. green office buildings population.

5.8 Summary

This chapter described the data collection procedures and steps undertaken to satisfy data uniformity and quality for this research. Study response rate was also reported in this chapter. The study is continued with the data analysis methods in the next chapter starting with the quantitative data analysis approach.

Chapter 6

Quantitative Data Analysis

This chapter contains details on the quantitative analysis steps and presents the study results in three main sections. First, the descriptive statistics of the study sample are provided. Second, the univariate analysis results are explained, which show the basic relations between the high-performance green project delivery's dependent and independent variables. Lastly, the multivariate analyses of the process delivery attributes for the selected dependent variables are provided. The process delivery attributes at this phase include the independent variables selected from the univariate analysis phase and the control variables defined for the HPG project delivery. Multivariate analysis takes changes in the variables' effects into account after the models are adjusted for all variables. Therefore, it is the last and the most reliable step in the quantitative analysis phase of this study. However, the results of the quantitative analyses are significantly limited due to limited sample size, the extensive number of variables to be examined to understand the evaluation metrics, and the significant extent to which some of the variables are associated with other variables. The chapter concludes with a power analysis to predict the sample size for future research studies, in order to overcome the limitations described within this study and reach rigorous, statistically significant results.

6.1 Data Sets

While the project databases presented in Chapter 2 were all used in the collection of focus projects, Green Globes and the U.S. Green Building Council's green building databases, and Partnership for Achieving Construction Excellence (PACE) members were the primary sources in data collection on selected projects. Overall, 40 office building projects were included in this research. In addition to the majority of these projects, there were 3 retail banks, 2 government/civic structures with monumental finishes, 2 courthouses, 3 office buildings with laboratory additions, one office building with large-scale computing, and 2 office buildings with light industrial and warehouse additions. Of the projects collected, 92% were new construction and 8% are renovation.

The project size varied between 2,500 SF (retail bank branches) and 1,600,000 SF. The project size interval is given in Figure 6-1**.** Nearly half of the projects were less than 50,000 SF in size and about one-fifth were in the range of 50,000 to 150,000 SF. The last interval of the projects was in the range of 450,000 and 700,000 SF with one outlier in the sample that equaled 1,600,000 SF in size.

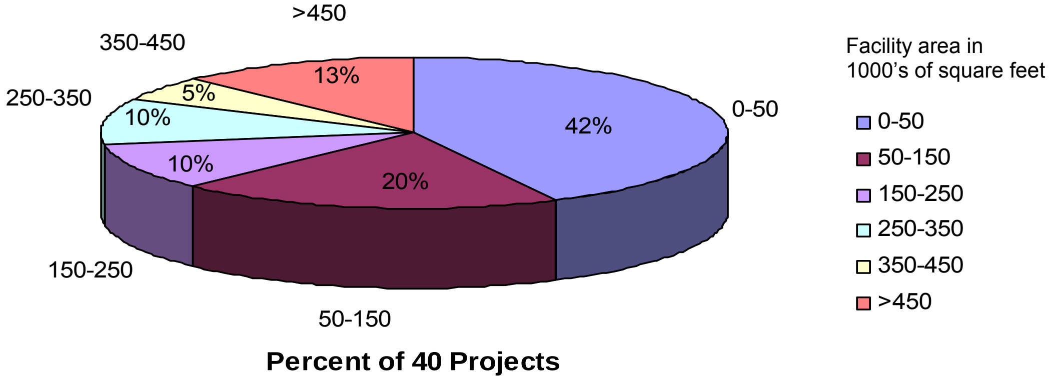


Figure 6-1**:** Percent of 40 projects by facility size

Figure 6-2 illustrates six unit cost intervals in which each interval represents $50 per SF except for the last interval. The unit cost intervals of the projects show that over one-quarter of the projects have unit costs between $100 and $150 per SF. The unit cost higher than $300 per SF is explained in the data set by facility characteristics such as small size, monumental finishes, or complex additions (e.g., laboratories).

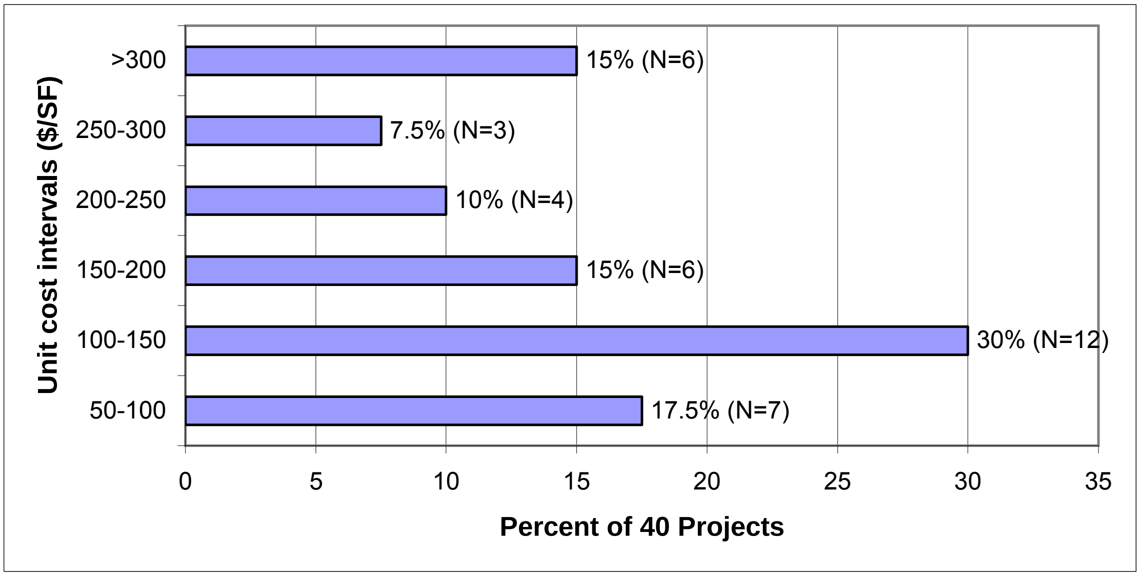


Figure 6-2**:** Percent of 40 projects by unit cost

The projects were constructed by three types of owners: public, private, and developers. Among these projects, 42% are publicly owned, 45% of them are privately owned, and the rest are constructed by developers. Primary owners occupy 85% of these buildings.

Of the study projects, 40% were delivered using the construction management at risk delivery method; 25% used the design-build; and 35% used the design-bid-build, establishing an unbiased sample for any of the project delivery methods.

6.2 Quantitative Data Analysis Methods

Quantitative analysis began with a preliminary exploratory data analysis and was followed by univariate and multivariate data analysis stages. This step in the data analysis was concluded with a power analysis to detect sample size for future studies. The following steps were used as guidelines:

1) Perform Exploratory Data Analysis (EDA) to reduce the number of predictors or categories within the variables. Use frequency tables to see if some options were rarely or never chosen. Remove the rare options by combining levels.
2) Categorize the independent, control, and dependent variables under continuous and categorical variable titles based on the level characteristics to measure them. Treat the ordinal variables that have more that 4 levels (originally, categorical variables) as continuous variables in the analysis procedure. Keep the nominal variables and the ordinal variables with fewer than 4 levels as categorical variables. Categorization of variables is essential when deciding which type of analysis to use in the study. The table presented in Appendix E summarizes the scale of measurement for the independent, control, and dependent variables in the study with regard to the survey questions.
3) Perform **univariate analyses** to reduce the set of independent variables.
    a) Conduct ANOVA to test the categorical independent variables for the following null hypothesis: H_0: Means of dependent variables are the same for different levels of various independent variables. Remove predictors that have a p-value greater than 0.2. Note the ones that have lower p-values than 0.05 (α=.05) to include in the prediction models and reject the null hypothesis for those variables.
    b) Use pairwise multiple comparisons (Tukey method) on the one-way ANOVA models to test the developed hypotheses and identify which levels of the various categorical variables statistically differ.
    c) Use regression analysis to test the associations between the continuous independent variables and the dependent variables for the following null hypothesis: H_0: The slope of the regression line equals to zero. Remove predictors that has a p-value greater than 0.2. Note the ones that have lower p-values than 0.05 (α=.05) to include in the prediction models and reject the null hypothesis for those variables.

4) Check residuals for normality and equal variances assumptions. Normal distributions and equal variance assumptions should be satisfied to conduct the analysis of variance (ANOVA) tests.
   a) Test whether the residuals comply with the normality assumption.
   b) Transform responses using log or power until normality is provided.
   c) Examine plots of means and standard errors of dependent variables.
   d) Investigate residual model diagnostics in cases where the normality assumption is violated. Consider log, inverse, inverse log, or root transformations for the model variables.
   e) Identify all "unusual observations" and explain their reason for being unique.
   f) Re-run the normality test for the residuals until it complies with the normality assumption.
   g) Test for equal variances at a confidence interval of 95%.
      1. Use Bartlett's test if the data are normally distributed.
      2. Use Levene's test if the data are continuously but not normally distributed.
5) Re-run the one-way ANOVA and regression analysis for the transformed variables.
   a) Develop the descriptive statistics for the significant independent variables that have p-values lower than 0.05.
   b) Plot graphs to illustrate the differences in the levels of the significant categorical independent variables and the relations between continuous independent and dependent variables.
   c) Report the independent variables that are significant ($p< 0.05$) and those that have the potential to be significant in future studies with larger sample sizes ($p< 0.2$).
6) Apply the Bonferroni correction to calculate a strict statistical significance level for each hypothesis tested in the univariate analysis.

7) Perform **analysis of covariance** (ANCOVA) to find the significant variables in HPG building project delivery by examining both the selected independent variables and the control variables for the selected dependent variables:
    a) Test for Ho: The covariate coefficient equals zero. Select the covariates that have p-values lower than .05.
    b) Test for Ho: All adjusted treatment means are equal to each other. Select the categorical variables that have p-values lower than .05.
    c) Test for the assumption of independent and homogenous normally distributed errors before deciding that the results are valid.
    d) Perform necessary transformations to satisfy the assumptions.
    e) Re-run the tests.
    f) Report least square mean values of significant categorical variables.
    g) Conduct Tukey pairwise comparisons to detect the means that are significantly different from each other.
8) Perform power analysis to predict future study sample size at power .80 and .90.

6.3 Univariate Analyses Results

Univariate analyses, as explained in detail in Appendix F, showed that various relationships exist between process indicators and performance outcomes in HPG project delivery. The results of these analyses should be reviewed carefully so as not to overemphasize outcomes since the study uses a limited sample size. However, the conducted analyses were helpful in screening the extensive number of independent variables in HPG building project delivery and limiting the set of variables to be examined in the multivariate analyses. Results also contributed to observations of relation patterns for process indicators and performance metrics. Until more robust analyses can be done on HPG project delivery, the outcomes of the study data can be used to increase understanding of HPG project delivery evaluation metrics.

After the univariate analysis results were reported, the Bonferroni correction was utilized. The Bonferroni correction is a method of calculating a stricter significance level for hypothesis testing when multiple tests of statistical significance are run using the same data. This procedure was utilized since at the 0.05 significance level, 5% of the hypothesis-tests might appear to be significant by chance. In the Bonferroni approach, the alpha should be multiplied by $1/n$, where n represents the number of independent hypotheses run about a data set, to find the stricter value of the hypothesis significance level. Use of the new alpha would eliminate the significant relations that can appear due to chance. In this study, n equals 68; therefore, 0.001 was used as the stricter significance level in hypothesis testing.

As a result of the univariate analyses, the independent variables found to be significant ($p < 0.05$) in the univariate analyses, the significant variables according to the Bonferroni test ($p < 0.001$), and the variables with the potential to become significant in future studies with a larger sample size ($p < 0.2$) by affecting the dependent variables are reported in Tables 6-1, 6-2, and 6-3**,** respectively. Lessons learned from the summary tables are presented below.

The significant indicators are spread in the tables: Overall, the significance indicators for the hypotheses show a spread pattern (see Tables 6-1, 6-2, and 6-3**)** which explains why many of these variables were found to be significant on the univariate analysis level or have the potential to become significant if more data are gathered. The spread pattern in the table reveals that the identified project delivery process indicators (independent variables) that could potentially impact the project performance outcomes were found to be meaningful when investigating HPG project performance outcomes.

Some significance indicators generate patterns: The dependent variables used to examine the project performance outcomes can exert different weight when evaluating success based on the project and owner priorities. The tables show that some of the significance indicators are grouped under specific dependent variables, illustrating some patterns. Interpreting these patterns can be useful as project teams’ focus on the process indicators associated with their project specific goals.

Table 6-1: Univariate Significance Levels Table for Independent/Dependent Variables–I

Project Delivery Attributes (Independent Variables)		Dependent Variables											
		Time Metrics			Cost Metrics			Quality Metrics			HPG Metrics		
		ConstSpd	DelSpd	SchGrw	UnitCost	Intensity	CostGrw	TurnQ	OvrlQ	SystQ	EnrgyRt	IEQRt	GrnRt
Owner Commitment	OwnType	◐	◐	o		o	◐						
	OccType	o	o		o		o						
	GrnLeader					o						o	o
	GrnReason						◐	o	o				
	GrnIntro	o	o				◐	o					
	GrnImp												o
	ProDel	o	◐						o		o		
Project Procurement	ProMetDes	o	o			o							o
	ProMetCo	o		o		o							o
	ProMetDB												
	ProMetMech	o	o		◐					◐			
	ProMetElect	o	o		◐					◐			
	Select Des			o			◐						
	Select Cont				o		◐						
	SelectDB			o									
	RFP Cost		o										
	RFP Asth		o		o	o		o	o				
	RFP Tech		o				o					◐	
	RFP Qua				o			◐		◐	◐		◐
Contract Cond.	ContractDes	o	o		o	◐		o		o			
	ContractCont	o	o		o	●	o			o			
	ContractDB			o				o					
	Green Cont					◐			o		o		
	ContRelGrDes			o			◐	◐				o	

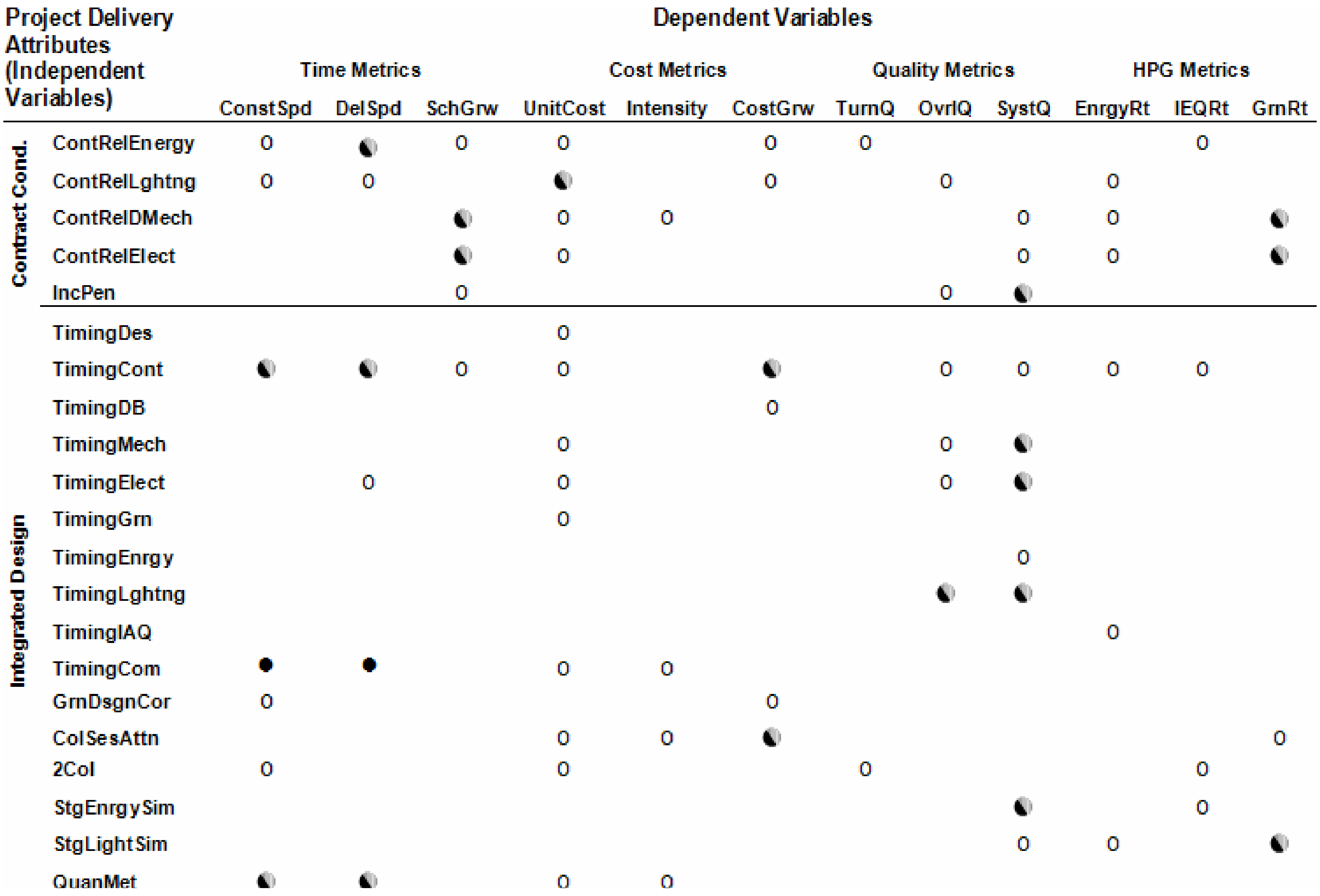
o : Represents potential for a significant relationship (p<0.2); ◐: Represents a significant relationship (p<0.05) ; and ●: Represents a significant relationship according to the Bonferroni test (p<0.001).

For example; Table 6-2 shows that methods used in the procurement of the project teams can affect the cost and time outcomes of the projects; contractual relations are associated with project intensity. Another example observed in Table 6-3 has to do with construction applications, which show potential relations mostly with the quality and high-performance green metrics. Lastly, Table 6-3 shows that experience levels of team members in similar facilities, high-performance green buildings, and project delivery methods have the potential to affect project time and cost performance. The univariate analysis results tables are useful in illustrating these patterns and can be used to guide project teams as they select process indicators that relate to their project-specific goals.

Some of the independent variables appear to have a good run over the table: The tables also show that some of the independent variables significantly affected most of the dependent variables. Timing of contractor's involvement in projects (see Table 6-2) and having a mock up for the envelope systems in projects (see Table 6-3) are the most significant examples of this trend in the univariate significance tables.

Additionally, the univariate analyses affirmed the most meaningful dependent variables in measuring HPG project delivery success based on the number of independent variables illustrated for each dependent variable. The selected dependent variables that were meaningful in defining HPG project delivery include: cost growth, construction speed, delivery speed, unit cost, energy rate, and green rate.

Table 6-2: Univariate Significance Levels Table for Independent/Dependent Variables–II



Project Delivery Attributes (Independent Variables)		Dependent Variables											
		Time Metrics			Cost Metrics			Quality Metrics			HPG Metrics		
		ConstSpd	DelSpd	SchGrw	UnitCost	Intensity	CostGrw	TurnQ	OvrlQ	SystQ	EnrgyRt	IEQRt	GrnRt
Contract Cond.	ContRelEnergy	o	◐	o	o		o	o				o	
	ContRelLghtng	o	o		◐		o		o		o		
	ContRelDMech			◐	o	o				o	o		◐
	ContRelElect			◐	o					o	o		◐
	IncPen			o					o	◐			
Integrated Design	TimingDes				o								
	TimingCont	◐	◐	o	o		◐		o	o	o	o	
	TimingDB						o						
	TimingMech				o				o	◐			
	TimingElect		o		o				o	◐			
	TimingGrn				o								
	TimingEnrgy									o			
	TimingLghtng								◐	◐			
	TimingIAQ										o		
	TimingCom	●	●		o	o							
	GrnDsgnCor	o					o						
	ColSesAttn				o	o	◐						o
	2Col	o			o			o				o	
	StgEnrgySim									◐		o	
	StgLightSim									o	o		◐
	QuanMet	◐	◐		o	o							

o : Represents potential for a significant relationship (p<0.2); ◐: Represents a significant relationship (p<0.05) ; and ●: Represents a significant relationship according to the Bonferroni test (p<0.001).

6.4 Multivariate Analyses

After the univariate analyses, the study moved to the next stage, multivariate analysis, to understand the adjusted effects of the independent variables on the selected dependent variables and which variables together would be able to explain the highest variability in the data set. The independent variables that were selected through univariate analysis and the control variables were analyzed for each selected dependent variable at the multivariate analysis stage. The selected dependent variables were: cost growth, construction speed, delivery speed, unit cost, energy rate, and green rate. Qualitative performance evaluation metrics (e.g., quality metrics) were not included in these analyses.

6.4.1 Procedure and Limitations

Use of analysis of variance using covariates (ANCOVA) is more suitable in cases in which an extensive number of variables with both categorical and continuous values are present (Garcia-Berthou, 2001). ANCOVA combines regression methodology with analysis of variance. It evaluates the effect of the covariates (continuous variables) on the response variable and enables the comparison of treatments (Kuehl, 2000). As summarized in Appendix E, this study presents a mix of categorical and continuous variables. Moreover, the intent of the study is to detect the independent variables that influence the dependent variables rather than developing prediction models. Therefore, ANCOVA is convenient for the multivariate analysis of the study variables. The two objectives of the ANCOVA tests were to:

1) Test whether the addition of the covariate (continuous variable) is significant in reducing the experimental error; and

Table 6-3: Univariate Significance Levels Table for Independent/Dependent Variables–III

Project Delivery Attributes (Independent Variables)		**Dependent Variables**											
		Time Metrics			**Cost Metrics**			**Quality Metrics**			**HPG Metrics**		
		ConstSpd	**DelSpd**	**SchGrw**	**UnitCost**	**Intensity**	**CostGrw**	**TurnQ**	**OvrlQ**	**SystQ**	**EnrgyRt**	**IEQRt**	**GrnRt**
Construction Appl.	CDPerctg									o	◐	o	◐
	SubsEd							◐				o	
	QWorkEnvlp									◐	◐		o
	QWorkMech							◐			◐		o
	QcontrolEnv	o	o										
	Qcont.Mech	◐	◐		o	◐			◐			o	
	Mockup	◐	◐			o	o		o		●		◐
Team Characteristics	ExpFacO						o		◐				
	ExpFacDB	o	o		o	◐			o				
	ExpFacSub	●	◐		◐	●						◐	
	ExpHPGO				◐	◐							
	ExpHPGDB				◐	o							
	ExpHPGSub	◐	◐			o							
	ExpProO				o		◐			◐			o
	ExpProDB	o			o								
	ExpProSub	◐	o		◐	◐	o						
	TemExp		o										
	TeamCom	o						o	o				
	TeamChem							o	●				
	Ocap				o				◐			o	
	Oscope	o	o					◐	o				
	Odecision												
	OComPre							o	◐	◐			
	Orestrain	o	◐				o			o			
	OTeamRel	◐		o		●	o	◐					

o : Represents potential for a significant relationship (p<0.2); ◐ Represents a significant relationship (p<0.05) ; and

●: Represents a significant relationship according to the Bonferroni test (p<0.001).

2) Test whether the treatment differences are significant based on the adjusted treatment means (treatment means are adjusted to the value of the significant covariate) (Kuehl, 2000).

The challenge this study faced at the multivariate analysis stage was the limiting of the sample size in order to produce results for the given set of independent variables. Each dependent variable was to be analyzed for an average of 30 independent variables (an average of 8 process indicators and 22 control variables), a mixture of categorical variables and covariates, some of which had up to 10 levels. It was not possible to run the ANCOVA for all of these variables at once and produce meaningful results due to the limited sample size. Therefore, the independent variables were added to the model in small groups and the number of variables was reduced each time by eliminating the insignificant variables from the models.

6.4.2 Results

The results for the multivariate analyses were generated based on the procedure described above. The presented objectives were achieved through examination of the p-values for the covariate and treatment means tests. The variables with p-values lower than .05 were eliminated from the models. Least square means of the dependent variables for each treatment and Tukey comparisons were also plotted for the models. The final outputs of these tests are presented in Appendix G. The p-values for testing the significance of the covariates are highlighted in these outputs and the results of the Tukey comparisons are given with the (a, b, ab) notation.

The ANCOVA results require the test of independent and homogenous normally distributed errors assumption (Kuehl, 2000). Inferences of ANCOVA regarding the green rate, unit cost, and intensity variables are not presented here due to their violation of the normality assumption. ANCOVA outputs (see Appendix G) show the covariates to be significant for the given dependent variables, and the categorical variables to have significantly different means according to their levels. These outcomes are summarized as follows:

1) Cost *Growth:* None of the covariates (continuous variables) were found to be significant. *Owner type* and *timing of contractor's involvement* in the project delivery process have significantly different means. Mean cost growth for public type of owners (10.01, SE 2.67) is larger (p< .05) than mean cost growth for private type of owners and mean cost growth for developers. Mean cost growth for public type of owners does not significantly differ from mean cost growth for developers. Mean cost growth for contractor's involvement in project delivery process at design development stage is larger (p< .05) than mean cost growth for contractor's involvement at the pre-design stage (1.23, SE 3.29), schematic design stage (1.31, SE 3.06), and bidding stage (5.62, SE 2.27). Mean cost growth for timing of contractor's involvement in the project delivery process at the design development stage is larger but not significantly different from the conceptual design stage (5.08, SE 4.26) and construction documents stage (7.44, SE 2.27).

2) *Construction Speed: Size* was a significant covariate for construction speed. ANCOVA showed a positive relationship between size and construction speed. *Owner type* and *timing of commissioning agent's involvement* in the project delivery process are the variables that have significantly different means. Mean log construction speed for developers (4.09, SE 0.16) is larger (p< .05) than mean log construction speed for private type of owners and mean log construction speed for public type of owners (3.69, SE 0.07). Mean log construction speed values for developer and public type of owners are not significantly different. Mean log construction speed for commissioning agent's involvement in the project delivery process at the conceptual design stage (3.11, SE 0.14) is lower (p< .05) than mean log construction speed for commissioning agent's involvement in the project delivery process at the pre-design (3.95, SE 0.14), schematic design (3.70, SE 0.10), design development (4.00, SE 0.12), construction documents (3.89, SE 0.14), and bidding (3.92, 0.15) stages.

3) Delivery Speed: Size was the only covariate found to be significant for delivery speed and to have a positive association with this dependent variable. *Owner type* and *timing of contractor's involvement* are the independent variables with different means. Mean log delivery speed for private type of owners (3.08, SE 0.11) is lower ($p < .05$) than mean log delivery speed for private owners (3.53, SE 0.11) and mean log delivery speed for developers (3.95, SE 0.26). Mean log delivery speed for contractor's involvement in the project delivery process at conceptual design (4.13, SE 0.21) is larger than at pre-design (3.61, SE 0.19) and larger ($p < .05$) than at schematic design (3.00, SE 0.16), bidding (3.01, SE 0.17), design development (3.42, SE 0.22), and construction documents (3.86, SE 0.17) stages.

4) *Energy Rate:* Completion rate of construction documents at the time of construction showed a negative correlation with the energy rate as a significant covariate. Building envelope mock-ups before the construction resulted in significantly different means: Mean energy rate for projects that did not include envelope mock-ups (60.73, SE 4.13) is larger ($p < .05$) than mean energy rate for projects that included envelope mock-ups (34.45, SE 5.57).

ANCOVA results show slight differences with univariate analysis results. The independent variable acquired from ANCOVA is stronger (with its means) since ANCOVA takes other variables into account while adjusting its results. However, it is important to understand the limitations of this research in conducting multivariate analyses. In the case of nominal independent variables, not all categories have data or adequate numbers of observations to enable their inclusion in a prediction model.

6.5 Power and Sample Size Analysis

The results and the limitations of the quantitative analysis of this study align with the expectations of exploratory research. Power analysis is essential to predicting the sample size needed for future studies of this nature in order to eliminate this study's limitations. Several power analyses were conducted for this study; two of them were run for energy rate and cost growth and are presented here.

The sample size needed to detect 2%, 5%, and 10% mean *cost growth* differences for different *project parties that hold a contract with a green design coordinator* on a project team with a power of .8 and .9 at 95% confidence can be determined via Table 6-4 below.

Table 6-4**:** Power and Sample Size Analysis for Cost Growth by Contract Group

```
One-way ANOVA

Alpha = 0.05  Assumed standard deviation = 6.105  Number of Levels = 3


          Sample  Target                  Maximum
SS Means    Size   Power  Actual Power  Difference
     2.0     181     0.8      0.801052           2
     2.0     237     0.9      0.900239           2
    12.5      30     0.8      0.803644           5
    12.5      39     0.9      0.902013           5
    50.0       9     0.8      0.839466          10
    50.0      11     0.9      0.914924          10
```

* The sample size is for each group.

The standard deviation in this calculation (6.105) is derived from the one-way ANOVA analysis results for cost growth by the party who holds a contract with a green designer coordinator. As shown in Figure 6-3**,** the number of projects needed to detect a 5% difference between cost growth means for the party to hold a contract with a green design coordinator is 117, with a 0.9 power. Three levels exist for this categorical variable: none, owner and other.

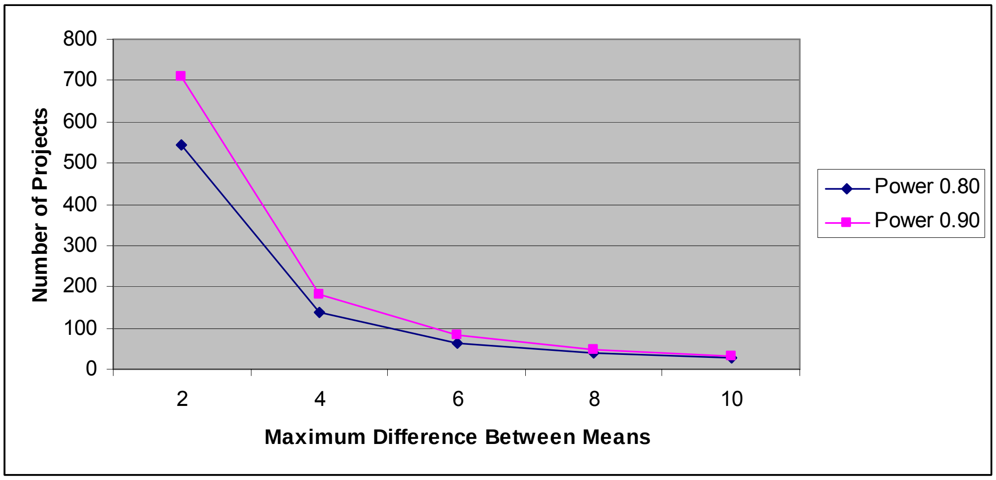


Figure 6-3**:** Power and number of projects for cost growth vs. contract with green design coordinator

As another example, the sample size needed to detect 5%, 10%, and 20% mean *energy rate* differences for different *project parties that are responsible for achieving "green" objectives according to their contracts* with a project team with a power of .8 and .9 at the 95% confidence can be determined via Table 6-5. The number of projects needed to detect a 10% difference between mean energy rates for this independent variable is 510 (102 multiplied by 5), for a 0.8 power. It is important to remember that this independent variables consists of 5 levels.

Table 6-5**:** Power and Sample Size Analysis for Energy Rate by "Green" in Contract

```
One-way ANOVA

Alpha = 0.05  Assumed standard deviation = 20.5  Number of Levels = 5


          Sample  Target                  Maximum
SS Means    Size   Power  Actual Power  Difference
    12.5     403     0.8      0.800879           5
    12.5     519     0.9      0.900083           5
    50.0     102     0.8      0.803254          10
    50.0     131     0.9      0.901413          10
   200.0      27     0.8      0.816541          20
   200.0      34     0.9      0.906481          20
```

* The sample size is for each level.

As illustrated in the power and sample size analyses above, larger sample sizes yield the desired levels of statistical power in HPG building project delivery research. Therefore, essential subjects of future research include efforts to effectively collect data, methods to maximize study the response rate in this area, and alternative methods of analyzing limited research data.

6.6 Summary

This chapter examined the associations between project delivery attributes and performance outcomes in HPG building project delivery using univariate and multivariate analysis techniques. The analyses contributed to understanding of screening evaluation metrics; observing relation patterns among variables; and selecting meaningful variables to ensure aggressive data collection efforts in future studies. The results show that the process indicators defined for this research are useful evaluation metrics for defining HPG building project delivery research. Despite the lack of significance in most of the analysis results due to the limitations of the study, findings from the quantitative data analysis were helpful in expanding knowledge of the HPG building project delivery.

Some of the associations found in the quantitative data analysis contradicted the theoretical background. These associations are summarized in Table 6-6. More in-depth investigation of these variables is needed after additional variables are included in the set of HPG project delivery metrics for more reliable investigation. A larger sample size might also provide a better understanding of these relationships.

Table 6-6**:** Summary of the Observed Unexpected Relations in the Quantitative Data Analysis

Dependent Variable	**Independent Variable**	**Nature of the Observed Association**
Unit Cost	Experience-Owner-HPG	Positive
	Experience-Design Builder-HPG	Positive
Intensity	Experience –Subcontractors-Facility	Negative
	Experience –Subcontractors-HPG	Negative
	Experience –Subcontractors-Project	Negative
Cost Growth	Timing of Green Introduction	*
System Quality	RFP-Quality	Negative
Energy Rate	RFP-Quality	Negative
	CD Completion Rate	Negative
	Mock-up	Negative
Indoor Environmental Quality	Experience-Subcontractor-Facility	Negative
Green Rate	RFP-Quality	Negative
	Mock-up	*

* Cannot be defined accordingly since the independent variables are categorical types.

The multivariate analyses conducted in this research were limited by the missing values in the data set and by the small sample size. The power analyses illustrated the need for a large sample to ensure a quantitatively rigorous HPG project delivery study. Future study should focus on data collection efforts to realize the sample size needed for this research. The power analysis confirmed the importance of this research in defining evaluation metrics and developing data collection tools and methods to maximize response rate. As an exploratory research effort, this study continued with the qualitative data analysis in order to triangulate the findings from the quantitative analysis, explain some of the unexpected outcomes using the case study approach, and draw additional lessons learned from the exemplary projects.

Chapter 7

Qualitative Data Analysis

The second step in the mixed-method strategy was to engage in a qualitative data analysis phase. This phase was conducted to support the findings from the quantitative data analysis, learn additional lessons from the collected data pool based on case studies, and define additional variables and data analysis methods for high-performance green (HPG) building project delivery that were not captured previously in this study. In this chapter, the researcher explains the tactics taken to satisfy the research design quality criteria, qualitative data collection techniques employed in this study, qualitative methods used to examine the data, and the results.

7.1 Research Design Quality

Four design tests are important in ascertaining research design quality: construct validity, internal validity, external validity, and reliability (Yin, 2002). This research satisfied the qualitative research design quality criteria by employing the following case study tactics:

1) For construct validity, this research used multiple sources of evidence (data triangulation), such as records of the survey data, interview recordings, and archival data (e.g., case study publications/reports on the media, and green certification score cards). The research also established a chain of evidence.
2) The researcher performed pattern matching to ensure internal validity, and compared and combined the patterns observed among several case studies.
3) Theoretical replication logic was used to enable external validity in the selection of good and bad case study projects.
4) A case study database was constructed to satisfy the reliability criteria.

7.2 Data Collection

The data collection phase of the case study approach followed the three principles of data collection: multiple sources of evidence, creating a case study database, and maintaining a chain of evidence (Yin, 2002). Multiple sources of evidence are used in case study data collection to enable data triangulation and ensure construct validity. The sources of evidence for the case study data collection were: (1) Documentation (e.g., LEED certification submission documents); (2) Archival records (e.g., project database created after data collection through online survey, web-based and published green case studies); and (3) Interviews with key project participants.

The collected data were recorded simultaneously in a coded format on an Excel^{TM} spreadsheet to satisfy the reliability criteria for case study research quality. Case study notes and case study documents cited in the notes were stored so as to be easily retrievable for later inspection.

A chain of evidence is desired in case studies to ensure construct validity and increase reliability. The chain of evidence was maintained in this case study approach by citing sufficient sources in the case study database, reflecting the actual evidence and the circumstances under which it was collected, aligning the evidence and circumstances with the case study protocol, and presenting the link between the study question and the case study protocol.

7.3 Case Study Data Evidence Analysis

The use of single and multiple case studies in generating high-quality qualitative research has been extensively discussed. Multiple cases are influential in theory building since they permit replication and validation of propositions through extension of theory among individual case studies (Eisenhardt, 1989). On the other hand, Dyer and Wilkins (1991) argued that single cases are more powerful than multiple case studies in creating high-quality theory. In this study, the multiple case study approach was utilized to achieve research goals.

Pattern matching and cross-case synthesis analytic techniques were performed to analyze the evidence in the case study approach. The pattern-matching technique was performed over multiple case studies and helped to ensure internal validity. Cross-case synthesis was another technique used to analyze the case study data in this research. This analysis primarily included performance comparisons of two sets of projects according to case study performance criteria. The process attributes of the two categories were recorded and compared to observe any difference in patterns. Results were reported to support or reject the quantitative analysis results and add to them where necessary. Case study evidence analysis steps followed in this research were as follows:

1) Perform pattern matching to ascertain whether process indicators can influence performance outcomes using similar case study pairs:
    a. Based on accepted practices used in estimating techniques, select case studies from the study database that are within 20% of each other’s size and cost to perform comparisons: This database includes 40 green office buildings. Seven pairs of projects fit the case study selection criteria.
    b. Assign scores to the performance metrics of the case studies using a qualitative scale (-1: Poor, 0: Average, 1: Good). Criteria to use in the assignment of scores to performance metrics were determined through examination of each dependent variable for performance metrics (see Appendix H).
    c. Categorize case studies based on their attributes under each process indicator.
    d. Determine whether any differences occurred in the sum scores of performance outcomes based on changes in the project delivery attributes.
    e. Perform pattern matching using different case study combinations.
2) Perform cross-case synthesis to enable comparisons between good and bad projects overall and determine whether good case studies present more of the project delivery attributes:

   a) Write the criteria to distinguish good projects from bad projects.
   b) Compare these two groups of case studies by marking the project delivery attributes that differ in good projects from bad projects.
3) Interpret findings and present observations.

7.4 Logic to Link Data with Expected Outcomes

Multiple case studies are used to link data to results. Evidence in the case studies that supports or contradicts the expected outcomes was collected and evaluated for this procedure. Evidence in the case studies was related to project delivery attributes. The criteria for the evaluation were based on evidence's potential to negatively or positively affect the performance outcomes of the HPG projects with regard to cost, time, quality, and levels of high-performance green metrics. Safety was eliminated from the data analysis due to the minimal response rate achieved for this metric.

7.5 Criteria for Interpreting the Findings

Two different approaches were followed for interpreting the findings in the case study evidence analyses.

7.5.1 Pattern Matching

In the first approach, the selected projects were assigned a representative score in each performance category. The collected evidence regarding the process indicators was categorized and interpreted by matching the evidence with the project scores. Scores within the performance categories and aggregate scores were used for each process indicator to interpret the findings. The criteria in favor of expected outcomes were based on the calculated score differences for the performance outcomes in the designed categories. An example of the method used to interpret the findings in this first approach, “Process Indicator #5—Integrated design”, is given in Table 7-1.

Table 7-1**:** The Criteria for Interpreting Findings for Pattern Matching

PI # 5 Design Integration	**Categories**	**Project Codes**	**Cost**	**Time**	**Quality**	**Levels of HP**	**Project Score**
More (+)	**1**	Project 1	1	0	1	1	4
Less (-)		Project 2	-1	-1	0	0	-2
More (+)	**2**	Project 3	0	1	1	0	2
Less		Project 4	0	-1	0	0	-1
More (+)	**3**	Project 5	1	1	0	0	2
Less (-)		Project 6	0	0	1	-1	0
				Total Score (+)			8
				Total Score (-)			-3

* Representative Scores: -1: Poor , 0: Avg, 1:Good

The case studies that were within 20% of each other’s size and cost were selected for these analyses. Seven pairs of projects were selected based on this criterion. The selected projects were coded and stored in Excel^{TM} spreadsheets. Criteria for assigning scores to performance metrics were determined after examination of each dependent variable for performance metrics as explained in Appendix H. Three dependent variables were used to determine each metric in this study. For example, cost growth, unit cost, and intensity were the dependent variables used to identify the cost metric. Descriptive statistics for each dependent variable were calculated to examine the mean and median values for the selected case studies. Histograms of these data sets were also plotted. Most of the data sets for the dependent variables were not normally distributed; therefore, decisions about the criteria to use in developing the scores were based on the histogram graphs. The average of the dependent variables’ representative scores under each metric was used to calculate the metrics’ representative scores.

After representative scores were assigned to the metrics, each project pair was examined based on their characteristics under process indicators to identify whether any differences could be found in the project performance outcomes based on changes in their characteristics. Selected projects were compared based on their overall project scores. The researcher decided that the case study evidence favored an expected research outcome (as defined earlier in Chapter 3) if the majority of the case study pairs supported the expected research outcome.

The overall scores of the projects that carried project delivery attributes in favor of an expected outcome were summed and assigned a "Total Score (+)" for that process indicator. The same approach was followed for the projects that had contradictory project delivery attributes with expected research outcomes: their total scores were assigned to the process indicators as "Total Score (-)". The difference between the total scores represented the importance of that process indicator to HPG building project delivery in potentially influencing performance outcomes.

7.5.2 Cross-Case Synthesis

The second approach used the following criteria to filter the best performing case study projects in the study database and develop two sets of case studies: Projects scored over 80% in high-performance green (HPG) categories and achieved less than 5% cost growth. Projects that scored less than 50% in HPG categories and had greater than 15% cost growth were considered to be poor performing projects. One case study that was an example of a good performing project and two that were poor examples were selected from the case study database for this analysis. Table 7-2 illustrates the methodology adopted to realize the cross-case synthesis on hypothetical case studies.

Table 7-2**:** Criteria for Interpreting Findings from Cross-Case Synthesis

Project Performance	**Project Codes**	**Project Delivery Attributes - Alignment w/ Propositions**						
		Owner Commit.	Project Delivery	Project Procure.	Contract Cond.	Integ. Design	Team Charac.	Constr. Appl.
Good	Project 1	√	√		√	√	√	
	Project 2	√	√	√	√	√	√	√
Poor	Project 3		√					√
	Project 4	√		√		√		

7.6 Results

As illustrated in Appendix H, the pattern-matching approach results provided support for four of the process indicators defined in this research for HPG building project delivery. The process indicators that the pattern-matching approach found to have a potential impact on HPG building project performance outcomes are presented below in the order of their importance. This ranking was generated based on the size of the difference between Total Score (+) and Total Score (-) for each process indicator.

1) Contract Conditions—Using negotiation of the team selection process, owners hold the contracts for primary project actors, and include “green” in contracts.
2) Owner Commitment—Being the driver of building “green” and introducing “green” early in the process.
3) Integrated Design—Early involvement of project participants and use of energy and lighting simulations in the process.
4) Project Delivery Systems—Construction management and design-build systems outperform design-bid-build.

The remaining process indicators were not rejected through the pattern-matching approach since the case studies did not yield contradictory results. However, due to the lack of positive evidence, the researcher determined that there was inadequate support for the remaining process indicators’ potential influence on performance outcomes in the selected case studies.

Cross-case synthesis of the good and poor performing case studies showed that about half of the project delivery attributes differed in two case study groups. These attributes all aligned with the expected research outcomes in the good case study. The process indicator-related characteristics observed in the good case study, as opposed to those in the bad case study projects, were as follows:

- “Green” achievement was an owner-driven pursuit in the good case study project, where it was mandated by the state or the client in the bad projects;
- “Green” was introduced early in the process (at the pre-design stage);
- Project delivery system used is: design-build;

- Sole source for selection of the design-builder, and the best value source for the mechanical and electrical contractors' selection were used rather than going for the lowest bid;
- The design-build team was selected through negotiation rather than lump sum;
- A design-build mechanical and electrical team was awarded the MEP package;
- Cost and technical aspects were the most important criteria listed in the request for design–build proposal, with quality rated as the least important criterion in proposal reviews, with project teams concerned about building features that would not directly contribute to project's long-term performance and that might be costly ;
- Achievement of the project "green" goals was inserted in the design-build team's contract;
- All important project parties, such as subcontractors, electrical and lighting consultants, and green design consultants, were contracted directly to the owner;
- All important project parties, including the commissioning agent and the consultants, were involved early on in the process (at the early design stages);
- The design process was highly integrated so as to utilize green design charattes at least twice with the involvement of all major project parties; and
- Simulation tools to increase the design efficiency toward high-performance features were utilized in the design process starting early on in the design. Energy simulation tools were used in the design process starting at the schematic design and lighting simulations were used starting in the conceptual design stage.

Cross-case synthesis did not help to detect any control variable patterns due to the large number of levels within those variables.

Open-ended questions within the applied survey and interviews conducted with the respondents also highlighted some of the research findings. In most of the projects, no matter how they performed, owners' commitment to "green" features of projects and the timing of introducing "green" to projects were among the most important process indicators of project success. Many of the respondents mentioned that the contractor's involvement early on in the process and the value engineering approach were essential in achieving projected HPG goals at lower budgets. Respondents also indicated that integrated design was one of the most highlighted process indicators in the qualitative approach. Additionally, design-build was pronounced to be an efficient project delivery system in contributing to the integrated design process and contractors' earlier input on projects was mentioned by most of the respondents. Several other process-related variables, some of which were already included in this study, were mentioned by at least one of the respondents. These variables can be summarized as follows:

- As a method of pursuing best value source selection in project teams' procurement, project green specifications should be included in the request for proposals and project teams that can commit to more of the characteristics within the given specifications at a given budget should be selected;
- Owners and designers' involvement in the construction process is important to guaranteeing that the construction applications fulfill the requirements;
- Separate consultants should test building envelopes for insulation, thermal and moisture resistance quality—this approach not only ensures the quality of the envelope but also motivates the construction teams to provide higher-quality applications;
- Design-build mechanical and electrical contractors should be hired as subcontractors to enable better HPG outcomes —their early involvement in the design process is important to assuring optimum mechanical and electrical systems designs at minimum cost; and
- Designers' and builders' relationship should not end right after construction completion. They should work with facility managers to ensure that the building is running at its maximum performance. Designers' and builders' input might be needed to upgrade buildings to their designed performance levels during the occupancy phase.

7.7 Summary

This chapter presented the qualitative analysis that was conducted in the second phase of the mixed-method strategy employed in this research. A description of the data collection techniques followed to generate a case study database, steps taken to conduct case study data evidence analysis, logic used to link the data to the results, criteria used in interpreting findings, and the results of the qualitative analyses were presented within this chapter.

Qualitative data analysis triangulated the results of the quantitative analyses. Results of these analyses showed that the defined process indicators in this research on HPG building project delivery are meaningful in generating better HPG project delivery performance outcomes. The results also provided qualitative data to support the expected outcomes and pointed to innovative techniques to be employed by the green construction community. The patterns observed at this phase of the research provide important lessons learned and can be generalized to the entire green building population in the future as more data are collected from the field.

Chapter 8

Summary and Conclusions

8.1 Summary of Findings

This study developed high-performance green (HPG) building project delivery evaluation metrics, collected US green office building data for the defined metrics, and pilot-tested them with mixed method, quantitative and qualitative approaches, analyses. Findings of the research are as follows:

1) *The results show that the defined evaluation metrics are useful in understanding HPG building project delivery.* The observed relationships within this research can be validated as the data emerges. As a pilot-study, this study successfully explored lessons to be learned about HPG building project delivery from the current green office building population in the US.

2) *The results of this research support the expected research outcomes:*

a) The quantitative analysis results supported by the qualitative analysis results show that the defined project delivery attributes can influence project performance outcomes in HPG building projects. More specifically:

- Timing of contractor's involvement in projects and using envelope mock-ups before construction are the strong independent variables affecting most of the performance outcomes.
- Only two of the defined independent variables proved to be insignificant for any of the dependent variables: procurement methods to select design-build team and owner's ability to make decisions. However, when combined with other variables (e.g., owner's capability, owner's ability to define the project scope) owner's ability to make decisions appeared to have significance for most of the performance metrics. Therefore, elimination of these variables from the set of HPG evaluation metrics is discouraged.

- Relation patterns exist between process indicators and performance outcomes: Procurement of project teams (PI #3) have the potential to affect cost and time outcomes of projects; contractual relations (PI #4) show potential associations with project intensity; construction applications (PI #7) show possible relationships, mostly regarding quality and high-performance green metrics, and last, team members' experience (PI #6) with similar facilities, high-performance green buildings, and the project delivery methods used have the potential to affect project time and cost performance.
- Findings support that the following independent variables under related process indicators have the potential to positively influence project performance outcomes:
    - Using negotiation for team selection process, contractual relations between owners and project participants, and including "green" in contracts (Contract conditions-PI #4);
    - Accepting the role as driving force for building "green" and introducing "green" early in the process (Owner commitment-PI #1);
    - Key project participants' early involvement in the process and use of energy and lighting simulations beginning early in the process (Integrated Design-PI #5);
    - Construction management and design-build systems outperforming design-bid-build (Project Delivery-PI #2).
- "Size" and "completion rate of construction documents at the time of construction" appear to be the only control variables to affect performance outcomes.

b) The qualitative analysis results show that exemplary projects exhibit a greater number of process indicators.

c) Online data collection tool is useful for collecting meaningful HPG building project delivery process data that can describe reliable metrics to affect project performance outcomes due to the tool's ease of reaching different project participants for a single project at the same time.

3) *The quantitative analysis approach assisted development of insights into performance metrics.* Cost growth, construction speed, delivery speed, energy rate and green rate are reliable performance metrics that can define HPG project delivery. On the

other hand, other metrics should be either improved or eliminated from the set of performance metrics since in this study, they were very useful with their current definitions.

Team characteristics and quality metrics are subjective metrics which are dependent on the respondents' levels of experience and feelings; therefore, they are not as reliable as the other objective metrics. Seeking alternative ways to measure team characteristics in HPG building project delivery research is worthwhile since the qualitative analysis pointed to the importance of team characteristics. As an objective way to measure this process indicator, asking project team members for their years of experience and roles with different type of facilities, project delivery methods, and HPG buildings is appropriate.

Although unit cost and intensity (which also uses unit cost) metrics are adjusted for year and location, their value is limited by the fact that the cost index does not consider construction types, systems used within buildings, or other control variables such as complexity. A remedy for this problem can be collecting cost information according to the system breakdown so that projects closer in scope can be combined for analysis purposes. However, this approach may be challenging in terms of achieving high response rates due to owners' cost data confidentiality concerns. This study includes control variables in the quantitative analysis, but did not discover significant results due to sample size. The same approach regarding the control variables should be followed in future studies.

HPG metrics in this research considered the percentage of achieved points in LEED among possible points in the LEED™ rating system. Non – LEED™ projects were also evaluated using the LEED™ criteria. However, other sections of the LEED™ rating system include criteria indirectly (positively or negatively) related to the energy and indoor environmental quality performance of buildings. Future research should focus on the rigorous examination of all direct and indirect energy and indoor environmental quality points in the LEED™ so that HPG metrics can be more comprehensive and reliable.

Schedule growth, indoor environmental quality metrics did not show many associations with project delivery attributes. Future research may consider eliminating these measures from the set of HPG evaluation metrics.

4) *Quantitative analyses pointed to several unexpected results regarding the relationships among some of the process indicators and performance outcomes.* As presented in Chapter 6, five of these results are associated with team experience related process indicators. This study recommends an alternative, an objective measurement of these indicators. Even though the alternative measurement was used for this metric, more in-depth examination with additional variables might be needed to understand these relationships in future studies. Additional insights were gained for the remainder of the observed, unexpected relationships in the qualitative data analysis stage:

a) Quantitative analysis yields a negative relationship between the importance of quality criteria in request for proposals (RFP) and system quality/energy rate. The “good case study” used for the cross-case synthesis resulted in the observation that this project had the lowest rating for quality in its RFP. The owner’s concern in this project was that project teams might have had a specific focus on building features that can have immediate results on owners’ perception of quality such as interior and exterior finishes rather than systems that would have long-term benefits like energy consumption and efficiency. In return they had high energy and system quality outcomes. However, widening the criteria to affect the results of this analysis in future research to understand the reasons for such a relationship is important.

b) Another unexpected result is the negative association between envelope mock-up and green rate of the buildings. The respondents from projects that had envelope mock-ups confirmed, in the qualitative data collection, that mock-ups were used to configure complicated design features for constructability reasons, and not necessarily for an testing envelope’s thermal or weather resistance performance.

c) Lastly, the negative relationship between the construction documents (CDs) completion rate and energy performance rate is explained by the evidence found in case studies. The projects with low CDs completion rate and high energy performance are delivered using design-build project delivery systems. This delivery system enables close integration between design and build parties and construction starts before completing the CDs. Therefore, construction professionals have a good understanding of the design at the time the construction starts, and completing of the related portions of the CDs can occur as the construction continues. To avoid such misunderstanding in the research findings, in future research, the related question should be either redesigned or the data analysis should be conducted separately for design-build projects.

5) *Additional process related variables were defined at the qualitative analysis phase of this study*. These variables are: inclusion of project green specifications in the request for proposals for project team procurement, need for working with suppliers when preparing specifications to ensure reliable construction estimates, emphasis on importance of design-build mechanical and electrical subcontractors to enable better performance at lower cost, involvement of designers and builders in the post-occupancy phase of buildings to assure the building operates maximum performance.

8.2 Contributions of the Research

Contributions of this research are four fold:

1) Evaluation metrics to define HPG building project delivery that includes project delivery process indicators and performance metrics: The research developed process indicators and performance metrics to measure and understand HPG building project delivery. These insights will enable the construction community to better discuss, benchmarks, and learn from HPG building projects.

2) A verified data collection tool and methods for feasible collection of meaningful data on HPG building project delivery: The designed survey is apparently useful for addressing the HPG building project delivery evaluation metrics. Several survey application strategies, presented below, solve the problems regarding data collection processes and increase survey response rate for future research:

a) To apply the survey in a web-based format: This strategy enables a user friendly format to send survey, receive answers, and record data. Extra efforts to mail or scan completed surveys apparently discouraged respondents' participation. Therefore, a web-based survey encourages interactive and motivated survey submission.

b) *To split the survey questions into parts according to their appropriateness for segments of project team members' interest:* This strategy enables a shorter list of questions for each of the project team members to answer. It eliminates the effort needed for a single respondent to contact other project participants (e.g. owner, architect, green design coordinator, mechanical contractor, general contractor) to provide the answers for the questions related to specific areas of expertise; thus each project participant needs to devote less time to complete the questions, and thereby eliminates the discouraging factors influencing survey completion.

c) To contact owners as the primary respondents: Receiving owners' perspective is crucial for HPG building project delivery research. First of all, several questions in the survey, such as team characteristics, project success, and project quality, are specifically designated for answers from only owners since these indicators and metrics are subjective. Second, an owner is the only party present during the whole project delivery process, so in most cases, only the owners are able to answer questions regarding project delivery processes. Third, continuing or possible future relationships between owners with the other project participants are essential for project teams. Therefore, owners' commitments and guidance for this type of study also motivate other project participants to become involved in the survey submission process. Last, essential project delivery data that might be confidential for project teams can only be obtained by the owners' permission. Receiving owners' approval would help increase response rate in project delivery field-studies.

3) *Methods to analyze collected HPG building project delivery data for defining project delivery attributes that lead to better HPG building project performance outcomes:* A mixed method was used for the data analysis in this exploratory research. The analyses began with a quantitative approach that utilized exploratory data analysis, univariate and multivariate data analyses. The research continued with a qualitative data analysis that supported the results of the quantitative approach, explained patterns that

could not be described by the quantitative approach, and provided additional lessons learned. The study's methodology proved to be useful for achieving its goals.

After gathering more data in the course of future research, a quantitative analysis approach can generate significant results. However, qualitative methods should always be apart of such studies to provide an additional method in HPG building project delivery research, since the green building market will evolve, over time, and innovative ideas project teams utilize to improve their project delivery processes may arise. Only qualitative methods can capture those new and innovative methods. Moreover, different project teams have different project goals. Using comparison techniques with case studies that have similar objectives would help project teams to select which delivery attributes to employ in their own projects. Therefore, use of mixed methods in HPG building project delivery research is extremely useful for expanding the knowledge base in this area.

Overall, this research provides pilot evaluation metrics and contributes to the literature with definitions of process indicators, control variables, and performance outcomes, a survey and strategies for data collection, and methods to analyze HPG building project delivery data. This study builds a foundation for future HPG project delivery research and provides a clear path for future research to follow.

8.3 Limitations of the Research

The green building market is still in its infancy and the population of green building projects is limited. The restricted size of HPG buildings in the market and time constraints for collecting data on these projects restricts the findings of this research. With the influx of more collected data on these projects, the relationships between process indicators and performance metrics can be verified to desired significance levels. Moreover, with a larger sample size, control variables can also be investigated.

Problems were identified regarding some of the defined evaluation metrics in this study. Their current use limited the findings of the study. However, alternative methods for approaching these metrics were defined and employing revised methods in future research can produce more reliable results.

Handpicking case study projects for qualitative data analysis from the database used for the quantitative analysis threatens the external validity of this study. Ideally, two different pools of projects should be used especially for verification purposes. However, the limited sample size and the minimal number of exemplary projects within the database inhibited following such an approach. Therefore, the results of this study should be reviewed with care to avoid overreaching its findings. The study findings do not validate the relationships between project delivery attributes and performance outcomes for HPG building projects, but instead explores evaluation metrics, increases the understanding regarding the HPG building project delivery attributes, and builds a foundation for future rigorous research.

8.4 Future Research

Future HPG building project delivery research should accept the lessons learned from this research regarding the evaluation metrics to add to the knowledge base in this area.

The power analyses presented in Chapter 6 confirm the need for a large sample size in HPG building delivery research in order to acquire rigorous results. Therefore, future research should first focus on developing a web-based data collection tool and a database for storing HPG build project data on an ongoing basis. This will allow capturing a large amount of projects' data from a variety of facilities. Developing the cumulative data base should apply strategies presented in this study to maximize response rates and provide sufficient information to enable rigorous research to validate the findings of this study.

A multivariate type of analysis should be used in the validation process to account for adjustments in models. Empirical models can then be used for developing owner and project team decision support tools to guide project delivery processes of HPG building projects. Last, analyses should be conducted using other types of facilities to see if significant evaluation metrics for HPG projects differ and lessons learned from these data sets can be utilized in all types of projects.

As the green market evolves and project teams become more experienced in HPG building project delivery, innovative approaches can change the way HPG buildings are delivered. Future research should utilize both quantitative and qualitative data collection and analysis approaches to capture the significant project delivery attributes for better performance outcomes as well as the innovative approaches project teams use in the field.

In a future web-based HPG database study, qualitative approaches can be utilized to enable project teams to view similar projects with similar goals and follow a parallel approach for their own project delivery processes. This will enable the construction community to learn from project delivery processes case studies with different project characteristics in terms of size, project performance goals, and facility types.

Summary tables to illustrate the quantitative analysis results, as in Chapter 6, are useful in showing relationship patterns between project delivery attributes and performance metrics. Therefore, these same factors can be used in future research and also by project teams in selecting the most important process indicators for achieving project specific goals.

Last, a non-response bias analysis should be performed in future studies to ensure that the sample of the study is representative of the population and allow the results to be generalized.

8.5 Concluding Remarks

The project delivery/pre-occupancy phase of buildings consists of important process indicators which are available for collecting data of the effective on the project performance and controllability by owners and project teams. The importance of process indicators increases in HPG buildings due to their complicated design and planning features. The development and organization of HPG project delivery process indicators will enable the construction community to better discuss, benchmark, and learn from HPG building projects.

The organization of the HPG building project delivery evaluation metrics is an important contribution of this research. The research findings show that process indicators and performance metrics presented in this research are useful for defining and examining HPG project delivery. In addition, the developed survey is an effective tool and applied data collection methods are useful for accumulating data of U.S. HPG building projects. The mixed methods design used for data analysis is the strength of this study: mixed method expanded the findings of the research and helped achieve its goals. Collected data were quantitatively examined and the results were triangulated with qualitative findings. This methodology generated a pilot assessment approach for exploring HPG building project delivery evaluation metrics. The procedures utilized in this research can be replicated in future research; also the findings can serve as lessons learned for the green construction community.

This research is timely since the green market in the US and the world is emerging and lack of project delivery specific research exists in this field. Future research should focus on collecting extensive data on HPG building projects and quantitative analysis of that information. As the population of the HPG buildings continues to expand the findings of this research can be verified and supplemented. Verification of these relationships will help to eliminate insignificant process indicators and performance metrics from the preliminary set of evaluation metrics. Collection of extensive HPG project data can also enable insights regarding the control variables. Validation of presented relations in this research through rigorous quantitative analyses will eventually help the green construction community to understand the most important HPG building project delivery process indicators that lead to improved HPG project performance outcomes.

The vision of this research, as the initial step in this area, is to collect data on an ongoing basis and provide a learning tool for the HPG community where project teams can enter their projects into a database early in the process and create customized processes based on lessons learned from other projects.

Bibliography

Abdi, H., (2007). "Bonferroni and Sidak corrections for multiple comparisons", in N.J. Salkind (ed.): Encyclopedia of Measurement and Statistics. Thousand Oaks, CA: Sage.

Alhazmi, T. and R. McCaffer (2000). "Project procurement system selection model", Journal of Construction Engineering and Management 126(3): 176-184.

Beard, J. L., Loulakis Sr., M.C., Wundram, E. (2001). “Design Build: Planning Through Development”, USA, McGraw-Hill.

Beheiry, S. M. A., Chong, W. K., and Haas, C. T. (2006). "Examining the Business Impact of Owner Commitment to Sustainability." J. Constr. Engrg. and Mgmt., 132(4): 384-392.

Bennett, J., Pothecary, E., Robinson, G., (1996). “Designing and Building a World Class Industry”. Reading, UK., University of Reading.

BOMA, (1991). “Statistical Abstract of the United States, Building Owners and Managers Association”, Report for Electric Power Research Institute.

Chan, A. P. C., Scott, D., and Lam, E.W. M. (2002). "Framework of success criteria for design-build projects", Journal of Management in Engineering 18(3): 120-128.

Chan, A. P. C. S. D., and Chan A. P. L. (2004). "Factors Affecting the Success of a Construction Project", Journal of Construction Engineering and Management 130(1): 153- 155.

CIB, (1999). “Agenda 21 on Sustainable Construction”, CIB Report Publication 237, Rotterdam, The Netherlands.

CIWM, (2006). "California Integrated Waste Management", http://www.ciwmb.ca.gov/GreenBuilding/CaseStudies/Commercial/Ridgehaven.htm, Accessed: 10/2006.

CIWMB, (2006). "California Sustainable Building Case Studies", http://www.ciwmb.ca.gov/GreenBuilding/CaseStudies/, Accessed: 10/2006.

Cohen, J., (1989). “Statistical Power Analysis for the Behavioural Sciences”, 2nd Ed, NJ: Erlbaum, Hillsdale.

DOE, (2003). Department of Energy, “The business case for sustainable design in federal facilities”, Washington, DC: Federal Energy Management Program.

DOE, (2006). Department of Energy, High Performance Green Project Database, http://www.eere.energy.gov/buildings/highperformance/, Accessed: 10/2006.

Dorsey, R. W., (1997). “Project Delivery Systems for Building Construction”,

Washington, D.C. Associated General Contractors of America.

Dyer, W.G. Jr. and Wilkins, A.L., (1991). “Better Stories, Not Better Constructs, to Generate Better Theory: A Rejoinder to Eisenhardt”, Academy of Management Review (16:3). Pp. 613-619.

EIA, (1995). "Energy Information Administration." http://www.eia.doe.gov/, Accessed: 10/2006.

Eisenhardt, K.M., (1989). “Building Theories from Case Study Research”, Academy of Management Review, 14: 532-550.

El Wardani, M., Messner J. I., and Horman M.J., (2006). "Comparing Procurement Methods for Design-Build Projects", ASCE Journal of COnrtruction Engineering and Management, 132(3): 230-238.

EPA, (2006). Energy Star Rating System, Environmental Protection Agency, http://www.epa.gov/, Accessed in 10/2006.

Fisk, W. J. (2000). "Health and productivity gains from better indoor environments and their relationship with building energy efficiency", Annual Review of Energy and the Environment 25(1): 537-566.

Fong, P. S.-W. and Choi, S. K.-Y., (2000). "Final contractor selection using the analytical hierarchy process", Construction Management and Economics, 18(5): 547-557.

Fowler, K. M., Solana, A.E., Spees, K., (2005). “Building Cost and Performance Metrics: Data Collection Protocol”, Pacific Northwest National Laboratory.

Garcia-Berthou, E., (2001). "On the misuse of residuals in ecology: testing regression residuals vs. the analysis of covariance", Journal of Animal Ecology 70: 708-711.

Gay, L.R., Mills, G.E., Airasian, P.W., (2005). “Educational Research: Competencies for Analysis and Applications”, Eight Edition, Pearson Education, Inc.,Pearson Prentice Hall, p.184-185.

GBA, (2006). "Improving the Business Case for Green Building: Towards a national data repository for self-reported metrics", Green Building Alliance Report, Private communication.

GBI, (2006). " Environmental Assessments for Buildings", Green Building Initiative, http://www.greenglobes.com/, Accessed: 10/2006.

Gransberg, D. D. and S. P. Senadheera (1999). "Design-build contract award methods for transportation projects", Journal of Transportation Engineering,125(6): 565-567.

GSA, (2004). “LEED Cost study: Final report”, General Services Administration, Washington, D.C., USA.

Hartkopf, V., Loftness, V. , Aziz, A., and Hua, Y. (2005). "Building as Power Plant (BAPP)", The AIA Journal of Architecture, September.

Hatush, Z. and M. Skitmore (1997). "Criteria for Contractor Selection", Construction Management and Economics, 15(1): 19-38.

Cho, Hee-Jae, (1997). http://www.socialresearchmethods.net/tutorial/Cho/intro.htm, Accessed: 10/2006.

Heerwagen, J. (2000). "Do Green Buildings Enhance the Well Being of Workers?", Environmental Design and Construction Magazine, July/August.

HMG, (1999). "Daylighting in schools: an investigation into the relationship between daylighting and human performance", Heschong Mahone Group, Report for Pacific Gas and Electric.

Holt, G. D. (1998). "Which contractor selection methodology?", International Journal of Project Management, 16(3): 153-164.

Horman, M. J., Riley, D.R., Lapinski, A.R. , Korkmaz, S., Pulaski, M. H., Magent, C., Luo, Y. , Harding, N. , Dahl, P. K. (2006). "Delivering green buildings: Process improvements for sustainable construction", Journ of Green Bldg., 1(1): 123-140.

IDS, (1998). “Integrated Delivery System for Sustainable Construction”, Salford University, Salford, UK.

IHP, (2001). "Indoor Health and Productivity", www.IHPCentral.org. Accessed: 10/2006.

Jennings, P. and G. D. Holt (1998). "Prequalification and multi-criteria selection: A measure of contractors' opinions", Construction Management and Economics, 19(6): 651-660.

Kats G., A. L., Berman A., Mills E. and Perlman J. (2003). "The Costs and Financial Benefits of Green Buildings", California, Report developed for Sustainable Building Task Force.

Kibert, C. (1994). "Establishing Principles and a Model for Sustainable Construction", Proceedings of the First International Conference on Sustainable Construction, Tampa, FL.

Kibert, C. J. (2005). "Sustainable Construction", New Jersey, John Wiley&Sons, Inc.

Kobet, B., Powers, W., Lee, S., Mondor, C., and Mondor, M., (1999). "PA High Performance Guide", Pennsylvania Department of Environmental Protection, Pennsylvania, USA.

Konchar, M. and Sanvido, V. (1998). "Comparison of U.S. project delivery systems" Journal of Construction Engineering and Management 124(6): 435-444.

Kuehl, R. (2000). “Design of Experiments: Statistical Principles of Research Design and Analysis”, 2nd edition. United States: Duxbury.

Lapinski, A. R. (2005). "Delivering sustainability: Mapping Toyota Motor Sales corporate facility delivery process", Department of Architectural Engineering, University Park, Penn State University. M.S. Thesis.

Lapinski A. R. , H. M. J., and Riley D. R. (2006). "Lean Processes for Sustainable Project Delivery", J. Constr. Engrg. and Mgmt., 132(10): 1083-1091.

Ling, F. Y. Y., S. L. Chan, et al. (2004). "Predicting performance of design-build and design-bid-build projects", Journal of Construction Engineering and Management 130(1): 75-83.

Loftness, V., Hartkopf, V., Gurtekin, Hua, B.Y. , Qu, M., Snyder, M., Gu, Y., Yang, X. (2002). "Building investment Decision Support (BIDS) ", ABSIC Research 2001-2002 Year End report.

Magent, C. (2005). "A process and competency-based approach to high performance building design", PHD Dissertation. Department of Architectural Engineering, University Park, Penn State University.

Mahdi, I. M., Riley, M. J., Fereig, S.M., Alex, A.P., (2002). “ A multi-criteria approach to contractor selection", Engineering, Construction and Architectural Management, 9(1): 29-37.

MCH, (2007). “McGraw-Hill Construction Education Green Building SmartMarket Report”, The McGraw-Hill Companies, Inc.

Milton, D. K., Glencross, P.M., Walters, M.D. (2000). "Risk of sick leave associated with outdoor ventilation level , humidification, and building related complaints", Indoor Air 10(4): 212-21.

Molenaar, K. R. and D. D. Gransberg (2001). "Design-builder selection for small highway projects", ASCE Journal of Construction Engineering and Management, 17(4): 214-223.

Molenaar, K. R., A. D. Songer, and Barash, M., (1999). "Public sector design-build evolution and performance", ASCE Journal of Construction Engineering and Management, 15(2): 54-62.

Molenaar, K. R. and A. D. Songer (1998). "Model for public sector design-build project selection", ASCE Journal of Construction Engineering and Management, 124(6): 467-479.

Morton, S. (2002). "Business Case for Green Design" http://www.facilitiesnet.com/bom/Nov02/Nov02environment.shtml, Accessed: 10/2006.

NCGreenBuilding, (2003)."North Carolina Green Building Technology Database", http://www.ncgreenbuilding.org/site/ncg//index.cfm, Accessed: 10/2006.

NIBS, (2005). "Whole Building Design Guide", http://www.wbdg.org/, Accessed: 10/2006.

NRC, (2006). "National Research Council", www.nrc.ca, Accessed: 10/2006.

Oyetunji, A. A. and Anderson, S. D. (2001). "Project delivery and contract strategy", Austin, TX, CII.

Palaneeswaran, E. and Kumaraswamy M. M. (2000). "Benchmarking contractor selection practices in public-sector construction - A proposed model", Engineering, Construction and Architectural Management, 7(3): 285-299.

Palaneeswaran, E. and Kumaraswamy, M. M. (2000). "Contractor selection for design/build projects", Journal of Construction Engineering and Management, 126(5): 331-339.

Riley, D., Magent, C. and Horman, M. (2004). “Sustainable metrics: a design process model for high performance buildings”, CIB World Building Congress. Toronto, CA.

Riley, D., and Horman, M. (2005). “Delivering green buildings: High performance processes for high performance projects”, Engineering Sustainability 2005: Conference of the Mascaro Sustainability Initiative, Pittsburg, PA.

Sanvido, V. E. and Konchar, M. D. (1997). "Project delivery systems: CM at risk, designbuild, design-bid-build", Austin, Texas, CII.

Seppanen, O. A., Fisk, W.J., Mendell, M.J. (1999). "Association of ventilation rates and CO2 concentrations with health and other human responses in commercial and institutional buildings", Indoor Air 9(4): 226-52.

Xenergy and SERA, (2000). "Green city buildings: applying the LEED rating system", Portland Energy Office, http://www.portlandonline.com/, Accessed: 10/2006.

Sieber, W. K., Staynor, L.T., MAlkin, R., Petersen, M.R., Mendel, M.J., Walligford, K.M., Crandall, M.s., Wilcox, T.G., Reed, L. (1996). "The National Institute for Occupational Safety and Health Indoor Environmental Evaluation Experience, part three: Associations between environmental factors and self-reported health conditions", Applied Occupational and Environmental Hygiene, 11(12): 1387-92.

Smith, A. (2003). "Building Momentum: National trends and prospects for high performance green buildings", Report by the U.S. Green Building Council for the U.S. Senate Committee on Environment and Public Works, Washington, D.C.

Songer, A. D. and Molenaar, K. R. (1996). "Selection design-build: Public and private owner attitudes", Journal of Management in Engineering, 12(6): 47-53.

Songer, A. D. and Molenaar K. R. (1997). "Project characteristics for successful public sector design-build", Journal of Construction Engineering and Management, 123(1): 34.

Sonmez, M., J. B. Yang, et al. (2001). "Addressing the contractor selection problem using an evidential reasoning approach", Engineering, Construction and Architectural

Management, 8(3): 20-30.

Thomas, S. R., Candace L. Macken, Tae Hwan Chung, and Inho Kim (2002). "Measuring the impacts of the delivery system on project performance - Design-build and design-bidbuild", Austin, TX, NIST.

Todd J.A., C., D., Geissler, S., Lindsey, G. (2001). "Comparative assessment of environmental performance tools and the role of the Green Building Challenge", Building Research and Information, 29(5): 324-335.

USCB, (2006). “Economic Census: Annual Value of Construction Put in Place in the United States”, U.S. Census Bureau, http://www.census.gov/econ/const/C30/total.pdf, Accessed: 3/2007

USGBC, (2007). “A National Green Building Research Agenda”, U.S. Green Building Council Research Committee, November 2007, Private Communication.

USGBC, (2006). U.S. Green Building Council. http://www.usgbc.org/, Accessed: 10/2006.

USGBC, (2002). "Building momentum: national trends on prospects for high performance buildings”, U.S. Green Building Council, Prepared for the U.S. Senate Committee on Environment and Public Works, http://www.eere.energy.gov/buildings/highperformance/design_approach.html, Accessed in 10/2006.

Vanegas, J. A., DuBose, Jennifer R., and Pearce, Annie R. (1995). "Sustainable Technologies for the Building Construction Industry Proceedings of the Symposium on Design for the Global Environment" Atlanta, GA.

Vesay, A. C. (1991). "A project delivery selection system", University Park, PA, Computer Integrated Construction Research Program.

WCED, (1987). “Our Common Future”, Brundtland Report, United Nations World Commission on Environment and Development.

Wong, C. H., Holt, G. D., and Cooper A.C., (2000). "Lowest price or value? Investigation of U.K. construction clients' tender selection process", Construction Management and Economics, 18(7): 767-774.

Yates, A. (2001). “Quantifying the Business Benefits of Sustainable Buildings”, Centre for Sustainable Construction, BRE.

Yates, J. K., Battersby, L. C. (2003). "Master building project delivery system and designer construction knowledge", Journal of Construction Engineering and Management, 129(6): 635-644.

Yin, R. K., (2002). “Case Study Research. Design and Methods”, Third Edition, Applied social research method series Volume 5, Sage Publications, California.

Yueldson, J., (2008). The Green Building Revolution, Island Press, Washington, Covelo, London.

Zimmerman, S., (2005). “Factors Associated with Referral Overrepresentation of African-American Students to Special Education”, Anne Arbor, MI, ProQuest Information and learning Company.

Appendix A

Power Analysis to Illustrate Project Delivery Research Characteristics

The power of a test is the probability to detect what we are looking for, given the sample size. The power of a test depends on the alpha (probability of type I error that is usually set to 0.05), the sample size, and the effect size. A larger sample size leads to higher levels of power. A analysis of power is important to perform at the preliminary stages of the study, in order to calculate how large of a sample size is needed to detect the desired effects. Determining the effect size can be achieved through experience and knowledge in the area or depending on previous data. Small, medium, and large effect sizes can guide the tests, in case the strength of the effect can be approximated (Cohen, 1989).

A power analysis to illustrate the sample size needed for this type of a study is performed using the previous project delivery study conducted at Penn State (Konchar and Sanvido, 1998). Minitab® statistical software was used to conduct the calculations. Cost growth (%) and delivery speed (SF/ Month) are among the performance metrics that were examined versus project delivery systems in the Konchar and Sanvido (1998) study. One-way ANOVA is firstly used to understand if the delivery system type influences cost growth and delivery speed. Hypothesis testing for cost growth versus delivery system resulted with a p-value of 0.006 (less than 0.05) which shows that delivery system is significant in predicting "cost growth". Tukey comparison output of the test showed significant difference between mean values of delivery systems 2 and 3 (representing design-build and design-bid-build). The use of this test enabled the researcher to identify the variance of the data and the effect size to be detected.

Standard deviation of 9.961 for the data, and the mean value differences between design-build and design-bid-build varying between 1.064 and 6.820 are important values from the previous data to be used in the sample size predictions of this study. Using this information, sample size to detect differences equal to 6 is calculated with a power of 0.80 (which is usually considered sufficient) and 0.90. Larger effect sizes (up to 20) are also considered to see the varying sample sizes. The results are illustrated in Table A-1 below.

Table A-1: Power and Sample Size for Detecting the Desired Levels of Difference Among the Cost Growth Mean Values for Different Project Delivery Systems

```
One-way ANOVA

Alpha = 0.05  Assumed standard deviation = 9.961  Number of Levels = 3

Means    Size   Power  Actual Power  Difference
    2     479     0.8      0.800014           2
    2     629     0.9      0.900111           2
    8     121     0.8      0.801752           4
    8     158     0.9      0.900104           4
   18      55     0.8      0.806863           6
   18      71     0.9      0.901034           6
   32      31     0.8      0.801476           8
   32      41     0.9      0.905641           8
   50      21     0.8      0.817951          10
   50      27     0.9      0.909963          10
```

* The sample size is for each level.

It is important to note that sample sizes are calculated and presented for each level in the table above. Therefore, in this study each sample size in the table should be multiplied by three to find the total sample size since there are three categories within this test: design-build; design-bid-build; construction management at risk project delivery system types. For example; sample size is 165 to detect a difference of 6% cost growth between different types of delivery systems with a power of 0.80 (Line 5 in the table above). The power analysis in this example shows that a large number of projects are needed to be included into the building project delivery research to reach the desired levels of significance in the results.

Appendix B

High Performance Green Building Project Delivery Survey (IRB # 26020)

RESPONDENT INFORMATION

Name : ____________________

Position/ Title : ____________________

Company : ____________________

E-Mail Address : ____________________

Phone Number : ____________________

Case Study Project Name : ____________________

SECTION I: PROJECT PROFILE

1. Please provide following information about the project:

(a) Project type: **i.** ☐ New Construction ☐ Renovation ☐ Addition
ii. ☐ Base Building ☐ Tenant

(b) Building use: ☐ Commercial ☐ Residential ☐ K-12 Education
☐ Higher Education ☐ Laboratory ☐ Health Care
☐ Other____________________

(c) Building Size: __________ / __________ SF (Total / Garage)

(d) Number of Floors: ____________

(e) Building Location: ________________ (City/ State)

(f) Who is the owner of the project? ____________________

(g) Type of Owner: ☐ Public ☐ Private ☐ K-12
☐ Higher Education ☐ Developer ☐ Other__________

(h) Who are the occupants of the project? ____________________

(i) Who initially proposed the idea of incorporating "green" or "sustainable" building attributes/ requirements?

☐ Owner ☐ Developer ☐ Designer / Design-Builder ☐ Other _______________

(j) Why is the project team pursuing green building objectives? (You can select more than one if needed.)

☐ Mandated by client or state
☐ Energy Use / Cost
☐Owner Driven Factor (Vision Statement)
☐Productivity of Occupants
☐Other____ (Please list)

(k) At what point during the design process was notion of a green building introduced? (Please base your timing definition on the level of design completed.)

☐ Conceptual Design (0-15%)
☐ Design Development (30-60 %)
☐ Bidding (Full CD)
☐ Schematic Design (15-30%)
☐ Construction Documents (60-99%)

SECTION II: PROJECT DELIVERY SYSTEM

2. Mark the appropriate box for the **project delivery system** which best describes that used on your project. (Use the definitions of project delivery systems below.)

☐ Construction Management at risk
☐ Design- Build
☐ Design-Bid- Build

CM at Risk: The owner contracts with a design company to provide a facility design. The owner separately selects a contractor to perform construction a management services and construction work in accordance with the plans and specifications for a fee. The contractor usually has significant input in the design process and generally guarantees the maximum construction price.
Design Build: This is a single agreement between an owner and a single entity to perform both design and construction under a single design build contract. Portions or all of the design and construction may be performed by the entity or subcontracted to other companies.
Design Bid Build: This is a traditional process in the US construction industry, where the owner contracts separately with a designer and a contractor. The owner normally contract with a design company to complete design documents. The owner or his/her agent then solicits fixed price bids from contractors to perform the work. One contractor is usually selected and enters into an agreement with the owner to construct a facility in accordance with the plans and specifications.

3. Mark the appropriate box for the **contractual terms** used for the design-builder or designer and contractor.

Architect/Designer	☐ Lump-Sum	☐ GMP	☐ Cost Plus fee	☐ Not Applicable
Contractor	☐ Lump-Sum	☐ GMP	☐ Cost Plus fee	☐ Not Applicable
Design-Builder	☐ Lump-Sum	☐ GMP	☐ Cost Plus fee	☐ Not Applicable

SECTION III: PROJECT PROCUREMENT

4. Mark the appropriate box for the **procurement method** used for the designer and contractor or design builder. (Use the definitions of procurement methods below.)

Architect/Designer ☐ Sole source selection ☐ Qualifications-based selection
☐ Best value source selection ☐ Fixed budget/best design ☐Low bid
☐Competition

Contractor ☐ Sole source selection ☐ Qualifications-based selection
☐ Best value source selection ☐ Low bid

Design-Builder ☐ Sole source selection ☐ Qualifications-based selection
☐ Best value source selection ☐ Fixed budget/best design ☐Low bid

Sole source selection: Direct selection without proposals.
Qualifications-based selection: Through an RFQ, the owner selects the most qualified designer/contractor and negotiates only with that entity to a "fair and reasonable" price.
Best value source selection: The designer/contractor entities respond with proposals that contain technical aspects and price; the owner selects the proposal it deems to be of best value.
Fixed budget/best design: The owner announces the budget for the project and the design-build teams compete by submitting proposals containing as much scope as they can place in their package.
Competition: Design only through competition w/out budget concerns.

5. Was the primary process for selecting the designer and contractors competitive or negotiated?

Architect/Designer	☐ Competitive	☐ Negotiated
Contractor	☐ Competitive	☐ Negotiated
Design-Builder	☐ Competitive	☐ Negotiated

6. What criteria in the **Request for Proposal** (RFP) were spelled out to be used in the design selection process? Please use the chart below to indicate the importance of the selection criteria.

Factors	**Most**			**Least**		**Factors**	**%**
	1	**2**	**3**	**4**	**5**		
A) Cost						A	
B) Design Aesthetics and Functionality						B	
C) Technical Proposal						C	
D) Qualifications						D	
E) Other……………………						E	
F) Other……………………						F	
						TOTAL	**100%**

7. When were the project participants contracted to the project team? (Please base your timing definition on the level of design completed.)

Project Participants	Predesign	Conceptual Design (0-15%)	Schematic Design (15-30%)	Design Development (30-60 %)	Construction Documents (60-99%)	Bidding (FullCD)
Core Team						
Designer						
Contractor						
Design-Builder						
Mechanical Sub.						
Electrical Sub.						
Consultants						
Green Design Facilitator						
Energy Consultant						
Lighting Consultant						
Indoor Air Quality Consultant						
Commissioning Agent						

Project Participants	Predesign	Conceptual Design (0-15%)	Schematic Design (15-30%)	Design Development (30-60 %)	Construction Documents (60-99%)	Bidding (FullCD)
Other key players (Please list below)						

8. Mark the appropriate box that defines the attributes of your project team:

(a) What was the ability to restrain contractor pool? ☐ Low ☐ High

(b) Was there a pool of qualified contractors? ☐ Yes ☐ No

9. Please select the procurement method used for **mechanical and electrical subcontractor services**: (Please refer to the definitions given in question 4.)

(a) **Mechanical Sub.** ☐ Sole source selection ☐ Qualifications-based selection
☐ Best value source selection ☐ Fixed budget/best design ☐Low bid

(b) **Electrical Sub.** ☐ Sole source selection ☐ Qualifications-based selection
☐ Best value source selection ☐ Fixed budget/best design ☐Low bid

SECTION IV: CONTRACT CONDITIONS

10. Were sustainability requirements a part of the contract and which party was responsible for conducting these requirements?

☐ No, sustainability requirements were not listed in the contract.

☐ Yes, architect was primarily responsible for it.

☐ Yes, contractor was primarily responsible for it.

☐ Yes, design-builder was primarily responsible for it.

11. What incentive clauses and/or penalties were included in the project? *(Please* ***circle*** *the choices in parentheses that apply.)*

☐ Quality (Incentive / penalty) ☐ LEED certification (Incentive / penalty)

☐ Schedule (Incentive / penalty) ☐ Energy Performance (Incentive / penalty)

☐ Cost (Incentive / penalty) ☐ Other ____________ (Incentive / penalty)

☐ Safety (Incentive / penalty) ☐ None

12. If applicable, who held the contracts for the project participants listed below? (Please check the relevant boxes)

	Contract Held by				
Project Participants	Owner	Architect	Contractor	Design-Builder	Not Applicable
Green Design Facilitator					
Energy Consultant					
Lighting Consultant					
Mechanical Contractor					
Electrical Contractor					

SECTION V: PROJECT SCHEDULE PERFORMANCE

13. Please provide the following schedule information.

Item	As Planned (mm/dd/yy)	As Built (mm/dd/yy)
Design Start Date (Notice to proceed)		
Construction Start Date (Notice to proceed)		
Construction End Date (Substantial Completion)		

SECTION VI: PROJECT COST PERFORMANCE

14. What are the following total project costs? Indicate whether estimated (E) or actual (A). Please deduct all property costs, owner costs of installed process or manufacturing equipment, furnishings, fittings and equipment, or items not a cost of the building.

Stage/ Cost	**Design Costs**	**Construction Costs**	**Total Project Costs**
Contract Award			
Final Cost			

Please estimate the cost of the site work (work done outside the footprint of the building as the percentage (%) final construction costs.__________________%

SECTION VII: PROJECT QUALITY PERFORMANCE

15. *If you are the **owner** please complete this section. If not please proceed to next section.*

Please evaluate the **quality** of the project compared to your expectations using a 1 to 5 scale.

Difficulty of facility start up:

☐ 1 (High) ☐ 2 ☐ 3 (Medium) ☐ 4 ☐ 5(Low)

Number and magnitude of call backs:

☐ 1 (High) ☐ 2 ☐ 3 (Medium) ☐ 4 ☐ 5(Low)

Did the quality of envelope/ roof/ structure/ foundation meet your expectations?

☐ 1 (Exceeded) ☐ 2 ☐ 3 (Met) ☐ 4 ☐5 (Did not meet)

Did the quality of interior space/ layout meet your expectations?

☐ 1 (Exceeded) ☐ 2 ☐ 3 (Met) ☐ 4 ☐5 (Did not meet)

Did the quality of environmental systems (light/ HVAC) meet your expectations?

☐ 1 (Exceeded) ☐ 2 ☐ 3 (Met) ☐ 4 ☐5 (Did not meet)

Did the quality of process equipment/ layout meet your expectations?

☐ 1 (Exceeded) ☐ 2 ☐ 3 (Met) ☐ 4 ☐5 (Did not meet)

Did the cost performance of the project meet your expectations (despite the growth, if any)?

☐ 1 (Exceeded) ☐ 2 ☐ 3 (Met) ☐ 4 ☐5 (Did not meet)

Did the project meet your expectations overall?

☐ 1 (Exceeded) ☐ 2 ☐ 3 (Met) ☐ 4 ☐5 (Did not meet)

If the building has received a green certification (e.g. LEED, Green Globes), please rate the **difficulty** of the submittal review process.

☐ 1 (High) ☐ 2 ☐ 3 (Medium) ☐ 4 ☐ 5(Low)

SECTION VIII: PROJECT HIGH PERFORMANCE CHARACTERISTICS

16. Please indicate any **certification** or **award** that the building received related to green or high performance attributes.

☐ LEED Certification__________ (Please indicate the year in the blank and the type below)

☐ LEED-NC : New commercial construction and major renovation projects

☐ LEED-EB : Existing Building Operations

☐ LEED-CS : Core and Shell Projects

☐ LEED-H : Homes

☐ Green Globes Certification ☐ SPiRiT ☐ Green Guide to Healthcare

☐ Energy Star ☐ Others________________________________

17. How important were the project's green goals for the project team?

☐ Very Important ☐ Fairly Important ☐ Not Important

18. Did the project meet the green goals that the team had set at the beginning of the project?

☐ Completely ☐ Partially ☐ Not sure

19. Please answer the following questions regarding building's high performance features:

(a) Which elements were used in the design to increase the energy efficiency?

☐ Shading ☐ Triple Glazing ☐ Occupancy Sensors

☐ Tinted Glass ☐ Radiant Heating Panels ☐ Radiant Cooling Panels

☐ Energy Efficient Lighting ☐ Heat pumps

☐Other____(Please list)

(b) What kind of heating system is used in the building?

☐ VAV ☐ Radiant Floor Heating

☐ Fan Boxes ☐ Underfloor Heating

☐ VAV Boxes with reheat ☐ Not sure

☐Other____(Please specify)

(c) What kind of boilers are used in the building?

☐ Cast Iron ☐ Membrane Watertube

☐ Electric ☐ Firebox

☐ Firetube ☐ Flexible Watertube

☐ Industrial Watertube
☐ Not applicable
☐ Vertical Firetube
☐ Not sure
☐Other____(Please specify)

(d) What kind of ventilation and cooling system is used in the building?

☐ Demand Controlled
☐ Dual Duct
☐ Water-side Economizer
☐ Radiant Cooling Panels
☐ Underfloor Cooling
☐ Dedicated Outdoor Systems
☐ VAV
☐ Air Side Economizer
☐ Chilled beams
☐ Not sure
☐Other____(Please specify)

(e) What kind of chillers are used in the building?

☐ Reciprocating Compression
☐ Screw Driven Compression
☐ Absorption
☐ Not applicable
☐ Centrifugal Compression
☐ Chilled beams
☐ Not sure
☐Other____(Please specify)

(f) How are the chillers piped within the building?

☐ Variable-Primary Flow
☐ Chillers in Parallel
☐ Not Applicable
☐ Primary-Secondary
☐ Chillers in Series
☐ Not sure
☐Other____(Please specify)

(g) Does the building include combined heat & power system? (on-site energy systems e.g. micro turbines, solar hot water systems)

☐ Yes ☐ No ☐ Not sure

(h) Does the building include entire façade continuity for vapor barrier?

☐ Yes ☐ No ☐ Not sure

(i) What energy efficient measures have been used within the mechanical system design? ☐

☐ Variable speed drives on pumps
☐ Variable speed drives on fans
☐ Enthalpy/heat wheels
☐ None
☐ Energy recovery ventilators
☐ High efficiency motors
☐ Not sure
☐Other________(Please specify)

(j) Was a mock up built for the envelope system of the building?

☐ Yes ☐ No ☐ Not sure

If your project is pursuing ***LEED certification*** *please answer the following question. If not, please proceed to* ***the next question*** **(Q.21)**.

20. Please provide the following information about initial and achieved LEED credits or you can also attach your preliminary and final LEED Checklist/ Scorecard.

SECTIONS	**EXPECTED POINTS**			**ACHIEVED POINTS** (Approved by USGBC)
	Yes	**No**	**Maybe**	
Site (TOTAL)				
Water (TOTAL)				
Materials & Resources (TOTAL)				
Energy & Atmosphere (TOTAL)				
Prerequisite 1 – Fundamental Building System Commissioning				
Prerequisite 2 – Minimum Energy Performance				
Prerequisite 3 – CFC Reduction in HVAC&R Equipment				
Credit 1 – Optimize Energy Performance				
Credit 2 - Renewable Energy				
Credit 3 - Additional Commissioning				
Credit 4 -Ozone Protection				
Credit 5 -Measurement and Verification				
Credit 6 -Green Power				
Indoor Environmental Quality (TOTAL)				
Prerequisite 1 – Minimum IAQ Performance				
Prerequisite 2 – Environmental Tobacco Smoke (ETS) Control				
Credit 1 - Carbon Dioxide (CO2) Monitoring				
Credit 2 – Increase Ventilation Effectiveness				
Credit 3 – Construction IAQ Management Plan				
Credit 4 –Low Emitting Materials				
Credit 5 –Indoor Chemical And Pollutant Source Control				
Credit 6 –Controllability of Systems				
Credit 7 – Thermal Comfort				
Credit 8 –Daylight and Views				

If your project is **NOT** ***LEED certified*** *please answer the following question. If not, please proceed to* ***the*** **SECTION IX**.

21. Please provide the following information about **energy performance** of the building.

(a) Involvement of a commissioning agent in the project team:

☐ Separate Consultant ☐ Contractor Self Performed ☐ No

(b) Existence of commissioning contract to review the building operation with operations and management staff: ☐ Yes ☐ No ☐Not sure

(c) Does the building design comply with ASHRAE/IESNA St. 90.1 (Energy Standard for Buildings) or the local code whichever is more stringent?

☐ Yes ☐ No ☐ Not sure

(d) Was a whole building simulation developed to reduce design energy cost compared to the energy cost budget for energy systems including HVAC (heating, cooling, fans, and pumps), service hot water and interior lighting?

☐ Yes ☐ No ☐ Not sure

(e) If yes, at what percentage was the design energy cost reduction achieved? ______(%)

(f) Existence of CFC-based refrigerants in HVAC&R* systems:

☐ Yes ☐ No ☐ Not sure

(g) Existence of renewable energy sources in building:

Photovoltaic systems ☐ Yes ☐ No ☐ Not sure
Wind power ☐ Yes ☐ No ☐ Not sure
Solar Hot Water Panels ☐ Yes ☐ No ☐ Not sure
Fuel cells ☐ Yes ☐ No ☐ Not sure
Other_______________________________________ (Please list)

(h) Existence of following equipment that ***does not contain HCFCs or Halons*****:

Base building level HVAC equipment ☐ Yes ☐ No ☐ Not sure
Fire suppression systems ☐ Yes ☐ No ☐ Not sure

(i) Existence of performance verification systems (metering equipment for):

Lighting systems and controls ☐ Yes ☐ No ☐ Not sure
Electric meter on a time result basis ☐ Yes ☐ No ☐ Not sure

Constant and variable motor loads ☐ Yes ☐ No ☐ Not sure

Chiller efficiency at variable loads ☐ Yes ☐ No ☐ Not sure

Cooling load ☐ Yes ☐ No ☐ Not sure

Gas or oil use meter on a time result basis

☐ Yes ☐ No ☐ Not sure

Air and water economizer and heat recovery cycles

☐ Yes ☐ No ☐ Not sure

☐ Other____(Please list)

(j) Was a grid- source, renewable energy (defined by Center for Resource Solutions) provided for the building through at least a two-year contract for at least 50% of the building's electricity?

☐ Yes ☐ No ☐ Not sure

* **CFCs:** Chlorofluorocarbons are hydrocarbons that deplete the stratospheric ozone layer.
HVAC& R: Heating, Ventilating, Air-conditioning and Refrigerating

** **HCFCs:** Hydrochlorofluorocarbons are refrigerants that cause significantly less depletion of the stratospheric ozone layer compared to CFCs.

Halons: Substances used in fire suppression systems and fire extinguishers in buildings that substances deplete the stratospheric ozone layer.

22. Please provide the following information about **the existence** of the following features in the project for **indoor environmental quality**.

Compliance w/ ASHRAE St.62* ☐ Yes ☐ No ☐ Not sure

Exposure of non-smokers to ETS** ☐ Yes ☐ No ☐ Not sure

Permanent Carbon Dioxide Monitoring System ☐ Yes ☐ No ☐ Not sure

Compliance w/ ASHRAE St.129* ☐ Yes ☐ No ☐ Not sure

Construction IAQ Management Plan:

- Sealing Ductwork ☐ Yes ☐ No ☐ Not sure
- Protection of on-site stored or installed absorptive materials from moisture damage ☐ Yes ☐ No ☐ Not sure
- Air Handlers during Construction ☐ Yes ☐ No ☐ Not sure
- Filters on the return ducts ☐ Yes ☐ No ☐ Not sure
- Replacement of filtration prior to occupancy ☐ Yes ☐ No ☐ Not sure

Use of Low Emitting Materials (Low VOC*** Content):

- Adhesives and Sealants ☐ Yes ☐ No ☐ Not sure
- Carpets ☐ Yes ☐ No ☐ Not sure

Furniture ☐ Yes ☐ No ☐ Not sure

Paints ☐ Yes ☐ No ☐ Not sure

Minimal pollutant of regularly occupied areas ☐ Yes ☐ No ☐ Not sure

Controllability of the Systems for **Occupants**:

Operable Windows ☐ Yes ☐ No ☐ Not sure

Ventilation System Controls ☐ Yes ☐ No ☐ Not sure

Temperature Controls ☐ Yes ☐ No ☐ Not sure

Lighting Controls ☐ Yes ☐ No ☐ Not sure

Provide Thermal Comfort:

Compliance with ASHRAE St.55* ☐ Yes ☐ No ☐ Not sure

Permanent temperature monitoring system ☐Yes ☐ No ☐ Not sure

Permanent humidity monitoring system ☐ Yes ☐ No ☐ Not sure

Daylighting:

Daylight Factor of 2% (min.) in 75% of all space occupied for critical visual tasks ☐ Yes ☐ No ☐ Not sure

Direct line of sight to vision glazing for building occupants in 90% of all regularly occupied spaces. ☐ Yes ☐ No ☐ Not sure

* **ASHRAE Standard 62:** Ventilation for Acceptable Indoor Air Quality

ASHRAE Standard 129: Measuring Air Change Effectiveness

ASHRAE Standard 55: Thermal comfort standards including humidity control within established ranges per climate zone w/ Addenda.

** **ETS:** Environmental Tobacco Smoke

*** **VOC:** Volatile Organic Compounds

SECTION IX: INTEGRATED DESIGN

23. Does the project have a designated "Green Design Coordinator" with relevant credentials or experience? ☐ Yes ☐ No ☐ Not sure

24. Was a collaboration session held during the design initiation stage to discuss sustainable goals? ☐ Yes ☐ No ☐ Not sure

25. If yes, who attended the session?

☐ Owner or owner's representative

☐ Architect

☐ Electrical Engineer

☐ Contractor

☐ Green Design Coordinator

☐ Mechanical Engineer

☐ Civil Engineer

☐ Other_________________________ (Please List)

26. What quantitative performance metrics does your team use to measure the sustainable performance of the project?

☐ Building Energy Use Intensity
☐ Lighting Power Density
☐ Net PV System Production
☐ Other______________________ (Please list)

27. Were at least two collaboration sessions held before the preparation of construction documents (not including the project initiation stage session)?

☐ Yes ☐ No ☐ Not sure

28. At what stage of the design were energy simulations used?

☐ Not used ☐ Schematic Design ☐ Conceptual Design
☐ Design Development ☐ Construction Documents ☐ After Bidding ☐ Not sure

29. At what stage of the design were lighting simulations used?

☐ Not used ☐ Schematic Design ☐ Conceptual Design
☐ Design Development ☐ Construction Documents ☐ After Bidding ☐ Not sure

30. Was a mock up built for the envelope system of the building?

☐ Yes ☐ No ☐ Not sure

SECTION X: PROJECT TEAM CHARACTERISTICS

31. Mark the appropriate box for each of the following attributes of your project team.

(a) Individual experience of team members with **<u>similar facilities</u>**:

Owner's Representative	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Design-Builder	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Architect/Designer	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Contractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Mechanical Subcontractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Electrical Subcontractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)

(b) Individual experience of team members with **<u>high performance green buildings</u>**:

Owner's Representative	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Design-Builder	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Architect/Designer	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Contractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)

Mechanical Subcontractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Electrical Subcontractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)

(c) Individual experience of team members using your project's **delivery system:**

Owner's Representative	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Design-Builder	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Architect/Designer	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Contractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Mechanical Subcontractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
Electrical Subcontractor	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)

32. Please evaluate the following project characteristics:

(a) Team's prior experience as a unit:	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
(b) Project team communication:	☐1 (Excellent)	☐2	☐3 (Limited)	☐4	☐ 5 (None)
(c) Project team chemistry:	☐1 (Excellent)	☐2	☐3 (Adequate)	☐4	☐ 5 (Poor)
(d) Owner-project team relationship:	☐First-time		☐Partnering		☐Repeat
(e) Owner representative's capability:	☐1 (Excellent)	☐2	☐3 (Adequate)	☐4	☐ 5 (Poor)
(f) Owner's ability to define scope:	☐1 (Excellent)	☐2	☐3 (Adequate)	☐4	☐ 5 (Poor)
(g) Owner's ability to make decisions:	☐1 (Excellent)	☐2	☐3 (Adequate)	☐4	☐ 5 (Poor)
(h) Project complexity:	☐1 (High)	☐2	☐3 (Average)	☐4	☐ 5 (Low)
(i) Regulatory/ legal constraints:	☐1 (Many)	☐2	☐3 (Few)	☐4	☐ 5 (None)
(j) Onerous contract clauses:	☐1 (Numerous)	☐2	☐3 (Several)	☐4	☐ 5 (None)

SECTION XI: CONSTRUCTION DATA

33. To what extend were the construction documents (drawing and performance specifications) completed at the time of envelope and mechanical-electrical-plumbing (MEP) systems' construction? ____________________ (%)

34. Were the subcontractors educated for specific applications and practices needed for green rating and certification systems such as LEED?

☐ Yes ☐ No ☐ Not sure

35. Please rate the ***quality of workmanship*** for the envelope and MEP systems' ***construction*** using a 1 to 5 scale.

Envelope:	☐ 1 (Excellent)	☐ 2	☐ 3 (Adequate)	☐ 4	☐ 5(Poor)
MEP Systems:	☐ 1 (Excellent)	☐ 2	☐ 3 (Adequate)	☐ 4	☐ 5(Poor)

36. Who did the quality control inspections on site specifically for envelope and MEP systems' components? (Please check all that apply.)

Envelope: ☐ Owner ☐ Architect ☐ Project Manager (Contractor)
☐ Field Team ☐ Separate Consultant

MEP Systems: ☐ Owner ☐ Architect ☐ Project Manager (Contractor)
☐ Field Team ☐ Separate Consultant

37. If available please provide the safety records of the project on the following:

OSHA Recordable Incident Rate (RIR): ________________________________
DART Rate (Days Away/Restricted or Job Transfer Rate): __________________
Lost Time Case Rate (LTC): ____
Lost Work Day Rate (LWD): ____

38. For the following items please select the appropriate alternative in each category to identify the appropriate systems and/ or descriptors that apply to your project:

(a) <u>Foundation:</u>

☐ Slab on grade with spread footings
☐ Mat foundation
☐ Caissons, piles, or slurry walls
☐ Other_____________________

(b) <u>Structure:</u>

☐ Pre-engineered metal building
☐ Bar joists or precast planks on bearing walls
☐ Steel frame and metal deck
☐ Precast concrete frame and decks
☐ Cast-in-place concrete structure
☐ Complex geometry/mixed framing types
☐ Other_____________________________

(c) <u>Exterior Enclosure:</u>

☐ All glass curtain wall
☐ CMU, brick, or stone
☐ Cast-in-place exterior walls
☐ Metal panels
☐ Precast panels
☐ Other___________________

(d) <u>Architectural Interior Finishes:</u>

☐ Minimal (e.g. warehouse, factory)
☐ Corporate office
☐ Monumental building finishes (e.g. marble)
☐ Standard commercial office
☐ Clean room environment
☐ Other___________________

(e) Heating/ Cooling:

☐ Roof top units
☐ Central Plant
☐ Other____________________
☐ Split System
☐ Heating only
☐ Cooling only
☐ Ventilation only

(f) Electrical:

☐ Uninterruptible power supply
☐ General lighting and computer use
☐ Process equipment loads
☐ Electric heat
☐ Intensive computer use
☐ Security system
☐ Other____________________

(g) Controls:

☐ Direct digital controls
☐ Other____________________
☐ Pneumatic controls

(e) Site:

☐ Urban
☐ Suburban
☐ Other____________________
☐ Rural
☐ Existing utilities
☐ Existing roads
☐ Mass excavation

SECTION XII: PROJECT SUCCESS CRITERIA

39. Please list the criteria your organization uses to measure success and then mark the appropriate box to rank each as it applied to your project.

1.____

☐ Excellent ☐ Average ☐ Poor

2.____

☐ Excellent ☐ Average ☐ Poor

3.____

☐ Excellent ☐ Average ☐ Poor

4.____

☐ Excellent ☐ Average ☐ Poor

40. Mark the appropriate box to rate overall success of the project.

☐ Excellent ☐ Average ☐ Poor

SECTION XII: LESSONS LEARNED

41. List any lessons below you learned on this project about high performance green building delivery:

Could this project have been **delivered** better or more successful? How?

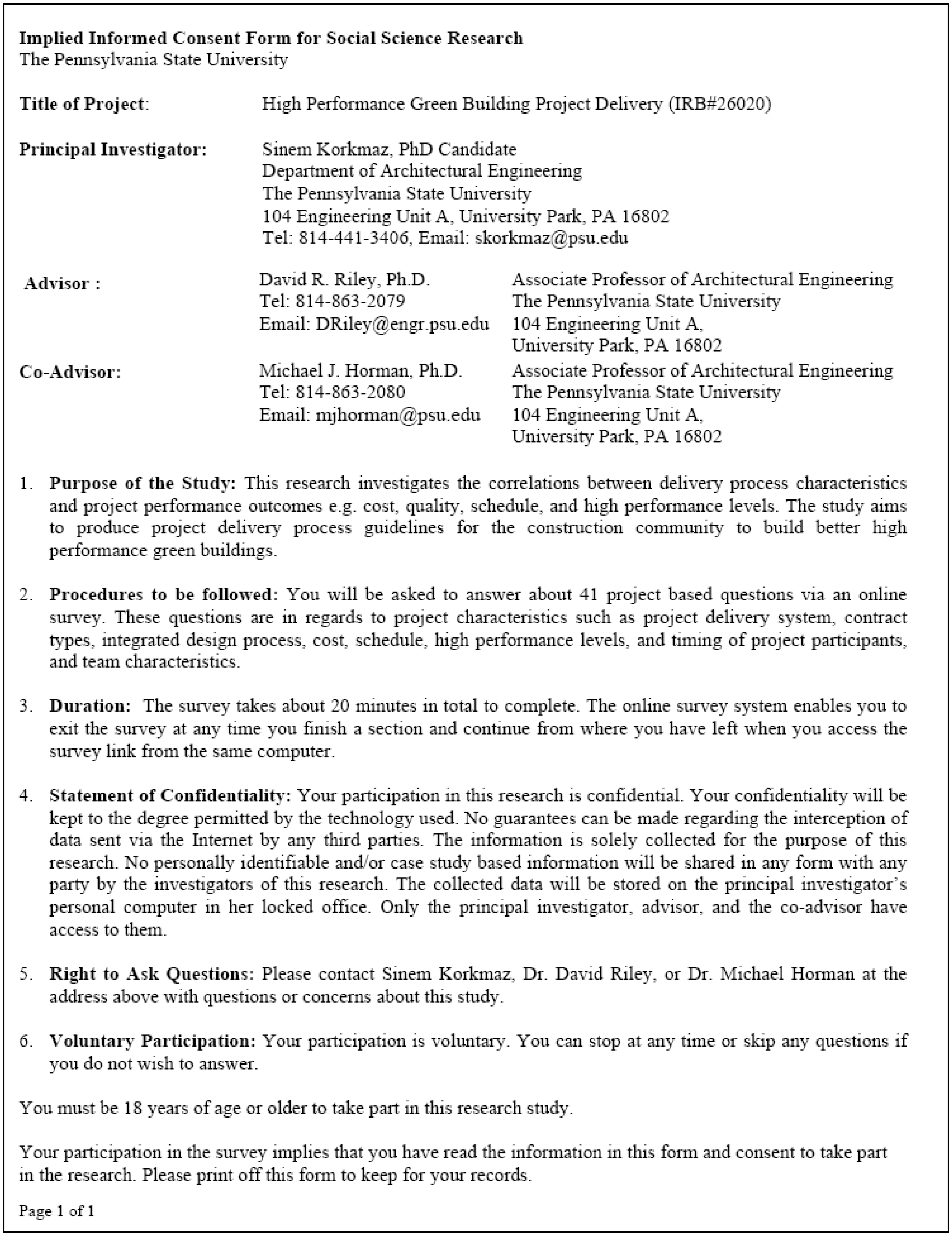
Did the delivery system enhance or hinder your ability to perform? How?

Did the project meet intended needs?

Describe any unique features about this building that influenced its cost, schedule or quality.

Appendix C

Informed Consent Form



Implied Informed Consent Form for Social Science Research
The Pennsylvania State University

Title of Project:	High Performance Green Building Project Delivery (IRB#26020)	
Principal Investigator:	Sinem Korkmaz, PhD Candidate Department of Architectural Engineering The Pennsylvania State University 104 Engineering Unit A, University Park, PA 16802 Tel: 814-441-3406, Email: skorkmaz@psu.edu	
Advisor :	David R. Riley, Ph.D. Tel: 814-863-2079 Email: DRiley@engr.psu.edu	Associate Professor of Architectural Engineering The Pennsylvania State University 104 Engineering Unit A, University Park, PA 16802
Co-Advisor:	Michael J. Horman, Ph.D. Tel: 814-863-2080 Email: mjhorman@psu.edu	Associate Professor of Architectural Engineering The Pennsylvania State University 104 Engineering Unit A, University Park, PA 16802

1. **Purpose of the Study:** This research investigates the correlations between delivery process characteristics and project performance outcomes e.g. cost, quality, schedule, and high performance levels. The study aims to produce project delivery process guidelines for the construction community to build better high performance green buildings.

2. **Procedures to be followed:** You will be asked to answer about 41 project based questions via an online survey. These questions are in regards to project characteristics such as project delivery system, contract types, integrated design process, cost, schedule, high performance levels, and timing of project participants, and team characteristics.

3. **Duration:** The survey takes about 20 minutes in total to complete. The online survey system enables you to exit the survey at any time you finish a section and continue from where you have left when you access the survey link from the same computer.

4. **Statement of Confidentiality:** Your participation in this research is confidential. Your confidentiality will be kept to the degree permitted by the technology used. No guarantees can be made regarding the interception of data sent via the Internet by any third parties. The information is solely collected for the purpose of this research. No personally identifiable and/or case study based information will be shared in any form with any party by the investigators of this research. The collected data will be stored on the principal investigator's personal computer in her locked office. Only the principal investigator, advisor, and the co-advisor have access to them.

5. **Right to Ask Questions:** Please contact Sinem Korkmaz, Dr. David Riley, or Dr. Michael Horman at the address above with questions or concerns about this study.

6. **Voluntary Participation:** Your participation is voluntary. You can stop at any time or skip any questions if you do not wish to answer.

You must be 18 years of age or older to take part in this research study.

Your participation in the survey implies that you have read the information in this form and consent to take part in the research. Please print off this form to keep for your records.

Page 1 of 1

Appendix D

Flyer for Data Collection Participant Recruitment

Delivering Green Buildings

A survey of the U.S. Green Office Buildings

Call for case study projects

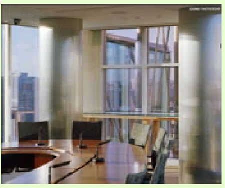
Share your experiences and help define the future of green building project delivery

Energy and Indoor Air Quality Performance

Quality

Cost

Schedule



Case Study Survey
is available online at
XXXXXX

The efficient delivery of high performance green buildings (HPG) represents one of the most important issues facing the industry today.

The Lean and Green research team at Penn State is pleased to announce a research effort to identify the project delivery attributes that are critical to the success of high performance green building projects.

Key Areas of Focus:

* Owners' Commitment
* Project Delivery Methods
* Project Team Procurement
* Contract Conditions
* Integrated Design Management
* Timing of Key Project Participants' Involvement
* Team Characteristics
* Construction Processes

Outcomes:

* Guidelines for owners and the project teams in the construction industry to better deliver HPG buildings.

* Common mechanical, electrical, and lighting system features of HPG buildings.

* A rigorous methodology to discuss, benchmark and learn From HPG case study projects.

Please submit
your project

to

**The Delivery of
HPG Buildings
Survey**

@

XXXXX

Contact Information:

Dept. of Architectural Eng.
Penn State University
104 Engineering Unit A
University Park PA 16802

814-441 3406
FAX: 814-863-4789

skorkmaz@psu.edu

A research effort
to identify the project delivery attributes
that are critical to the performance of
green building projects.

Research Question:
What project delivery attributes lead to improved green building outcomes in terms of cost, schedule, quality, safety and energy/indoor air quality performance?

Objectives:

- Collect data on project delivery attributes, sustainable performance, and project performance.

- Examine the collected data using qualitative and statistical techniques to identify relationships between project delivery processes, procurement methods and high performance levels, project cost, schedule, safety, and quality.

- Find common threads in project delivery among best performing projects.

Case Study Survey
is available online at
XXXXXXX

Appendix E
Scale Type of Survey Questions

Type of Scale	Independent Variables	Control Variables	Dependent Variables
CATEGORICAL	-Owner Type -Occupant Type -The party to propose “green” -The reason/reasons to go for “green” -Timing of introducing “green” -Importance of “green” for the project -Project delivery system -Procurement method -Primary process for team selection -Contractual terms used -Contractual relations -Contract incentives/penalties -Timing of participants’ involvement -Integrated design process -Use of quantitative metrics -Subcontractors’ education level on “green” -Quality Control -Mock-up -Ability to restrain the contractor pool -Owner team relation	-Existence of contractor pool -Project complexity -Mechanical System Characteristics -Building System Characteristics -Location	
CONTINIOUS	-Importance of criteria in RFP* -Construction Document’s level of completion -Quality of Workmanship* -Experience of the team members* -Team communication* -Team chemistry* -Owner’s capability* -Owner’s ability to define scope* -Owner’s ability to make decisions*	-Regulations/ Legal clauses* -Project Size	-Schedule Performance -Cost Performance -Quality Performance -HPG Performance -Safety -Overall Success

* Ordinal variables that have at least 4 levels are evaluated as continuous variables.

Appendix F

Report of the Univariate Analysis Results

Univariate analysis was conducted in this study to screen the extensive amount of HPG project delivery research variables. The screening process contributed to the study: (1) To determine the limited set of variables to be used in the multivariate analyses; and (2) To observe patterns to select the meaningful evaluation metrics for HPG building project delivery. Appendix F is devoted to explain the findings of the univariate analysis results of this research, in detail.

This section describes the relations of one independent variable with each dependent variable at a time. The means of the categorical independent variables in the data set were tested using one-way ANOVA (analysis of variance), while the continuous variables were examined using regression analysis. For each test 95% confidence level was used and the variables that only satisfy this confidence level (p value less than .05) were reported in this section. Tukey comparisons, a pairwise comparison to compare each treatment mean with each of the other treatment means, is also conducted under the one-way ANOVA procedure (Kuehl, 2000). The statistical analyses in this chapter were conducted using the Minitab® 15 statistical software.

Appendix F also summarizes the descriptive statistics for the significant variables and the Tukey comparison outcomes in metrics tables. The results of the mean tests are presented using a (9.26, SE 1.74) notation in this chapter, where the first value describes the mean and the second value reports the standard error of the mean. Additionally, (ab, a, b) designation is used to illustrate the Tukey comparison results in this thesis , where a and b represents significant difference between means and ab stands for insignificant difference of a treatment mean from the other treatment means. The number of observations for each level (N) is also presented in the results graphs in this section. Safety is the only dependent variable that was not included in the analyses due to a lack of data points collected.

The relations and the findings presented in this section should be reviewed with care since this study has a limited sample size. As seen in the graphs, the number of observations for many of the levels is very low. Moreover, the variability in mean values of these levels might be high. Additionally, some of the relations found at this stage of the data analysis might be due to chance since a very large set of variables was examined for each dependent variable. At this stage, univariate analysis method is not as reliable as the multivariate analyses in terms of making conclusions about the data set since it does not take all variables' effects into account in its comparisons. Therefore, the findings presented here are yet restricted to make generalizations for the whole HPG office building project population in the US.

On the other hand, the results presented in this section are useful for gaining insights about HPG building project delivery and increasing the researcher's understanding about the defined HPG evaluation metrics. The results also helped the researcher to select the significant variables to be entered in the multivariate analyses.

Univariate Time Results

The univariate time results are investigated for three dependent variables: construction speed (SF/Month), schedule growth (%), and delivery speed (SF/Month). As a result of the residual diagnostics, construction speed and delivery speed were transformed using log to satisfy the normality and equal variances assumptions. Figure F-1 shows that mean log construction speed for developers (4.26, SE 0.01) is greater ($p<.05$) than mean log construction speed for private owners (3.45, SE 0.14) and for mean log construction speed for public type of owners (3.70, SE 0.14). Mean log construction speed for developers does not differ significantly from mean log construction speed for public type of owners. These results align with the mean for log delivery speed for owner types. Therefore, we can conclude that developers build and deliver green office buildings faster than private type of owners.

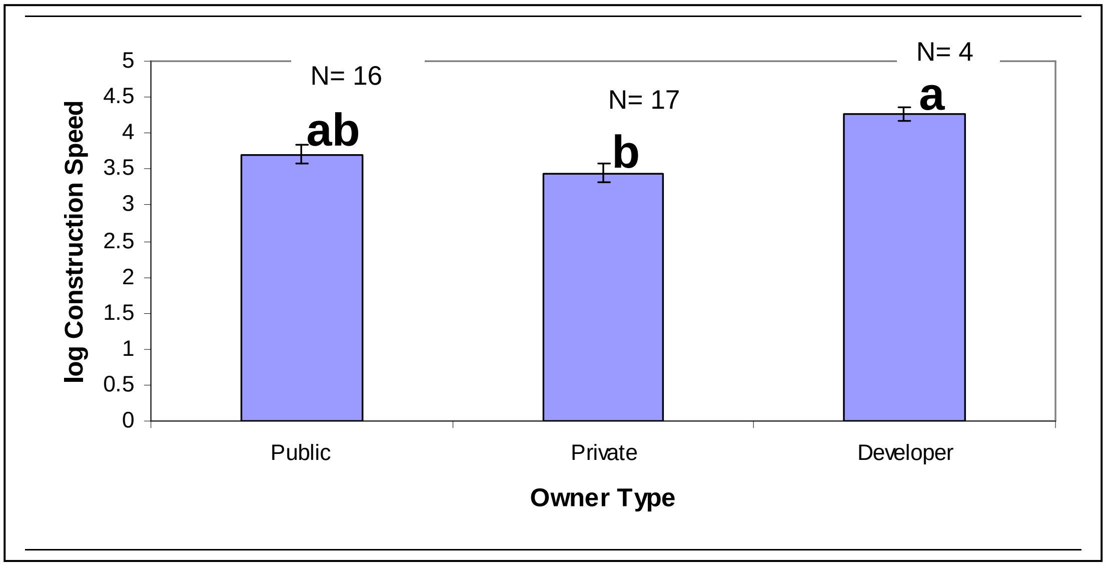


Figure F-1**:** Construction Speed by Owner Type

Timing of contractor's involvement is another independent variable that has different construction and delivery speed means according to its levels. The univariate analysis results indicate that the mean log construction speed for projects where the contractors are involved in the projects at the pre-design (4.159, SE 0.18) and at the design development stages (3.86, SE 0.35) are greater (p< .05) than mean log construction speed for projects where the contractor gets involved in the project at the bidding level (3.20, SE 0.18). Mean log construction speed for involvement in the pre-design and design development stages does not differ significantly from mean log construction speed for other design stages (see Figure F-2).

Mean log delivery speed for the timing of a contractor's involvement in the design process at the pre-design stage (3.97, SE 0.19) is greater (p< .05) than the mean log delivery speed for the timing of contractor's involvement in the design process at the bidding stage (2.89, SE 0.16). Mean log delivery speed for the timing of a contractor's involvement in the design process at the pre-design stage significantly differs from mean log delivery speed for the timing of a contractor's involvement in the design process at the bidding stage but not from other means for log delivery speed for the timing of a contractor’s involvement in the design process at other design stages. The results show a trend that earlier involvement of a contractor in the design process generates faster construction and project delivery.

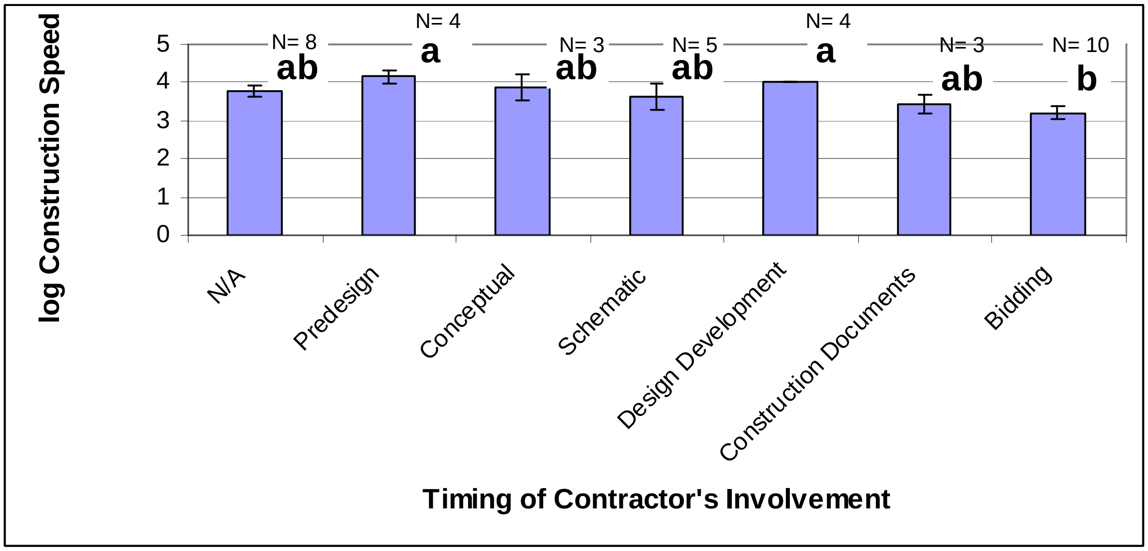


Figure F-2**:** Construction Speed by Timing of Contractor’s Involvement in Project Delivery Process

Contractual relations of mechanical and electrical subcontractors appeared to be important for schedule performance of HPG buildings in the univariate results. Figure F-3 illustrates that mean schedule growth for contractors as the party to hold a contract for mechanical and the electrical subcontractors (3.22, SE 2.3) is greater ($p<.05$) than mean schedule growth for designer (-24.2, SE 17.2) , for mean schedule growth for owners (-9.10, SE *), and for mean schedule growth for design-builders (2.23, SE 4.03). Mean schedule growth schedule growth for contractors as the party to hold a contract for mechanical and the electrical subcontractors does not differ significantly from mean schedule growth for owners and design-builders.

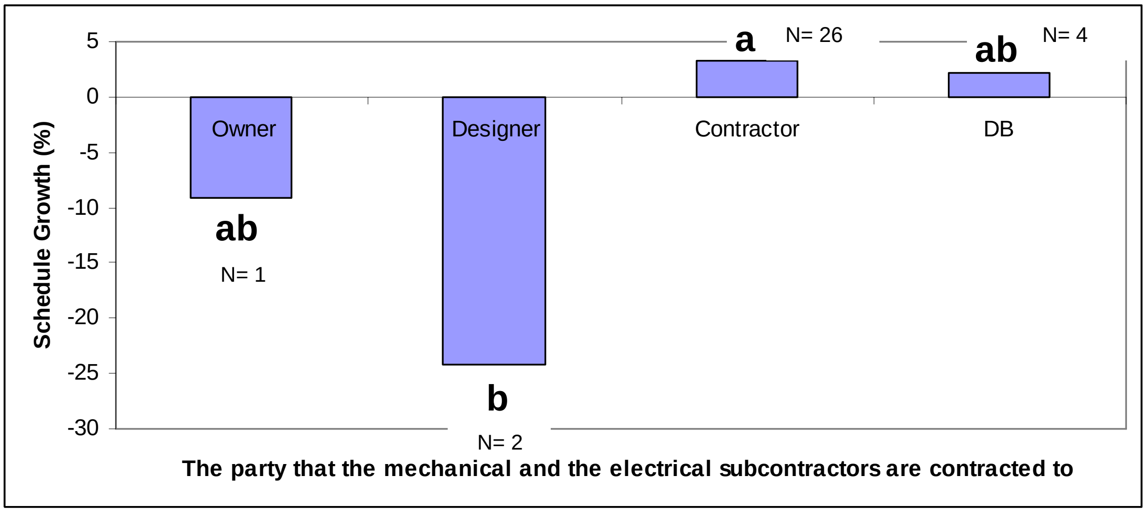


Figure F-3: Schedule Growth by Contractual Relations

Univariate results show that the use of *mock-ups* before the construction of the envelope systems can have a positive impact on both the construction and delivery speeds. For example, the mean log construction speed for projects that used mock-ups before the construction of the envelope system (3.90, SE 0.14) is greater ($p<.05$) than mean log construction speed for the ones that did not use mock-ups (3.45, SE 0.13).

The results also point to the importance of the *subcontractor's experience level* for faster construction and delivery: The level of mechanical and subcontractors experience with the facility type and high-performance green buildings shows a positive relationship with both log construction and delivery speed ($p<.05$). Subcontractors experience level with the project delivery method shows a positive relationship only with the log construction speed ($p<.05$) under the time metric.

The results indicate that construction management at risk and design-build outperforms design-bid-build in delivery speed. As presented in Figure F-4**,** mean log delivery speed for the design-build *project delivery system* (4.05, SE 0.09) and for construction management at risk (3.58, SE 0.18) are greater ($p<.05$) than mean log delivery speed for the design-bid-build type of project delivery system (3.03, SE 0.19).

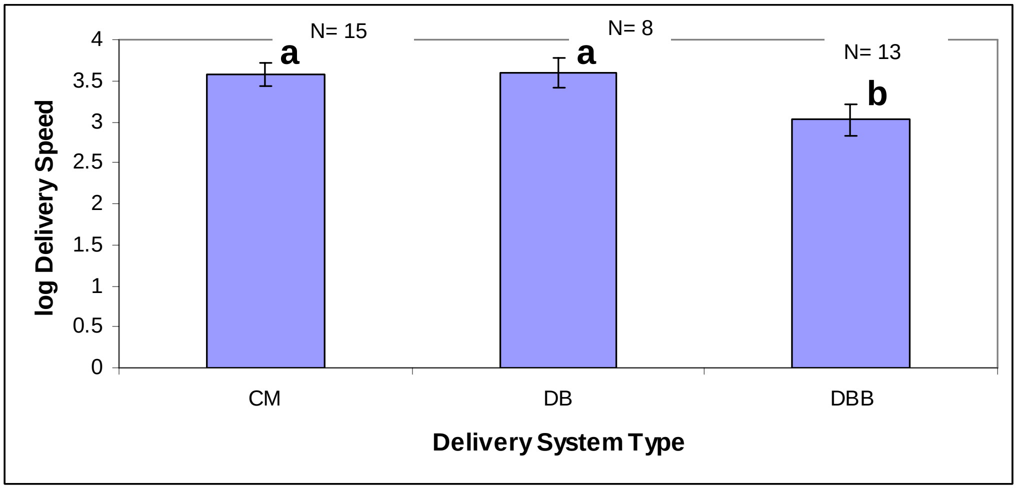


Figure F-4**:** Delivery Speed by the Delivery System Type

The *owner's ability to restrain the contractor pool* becomes important in selecting a qualified contractor and eventually for the delivery speed of HPG building projects. This outcome can be described as follows: Mean log delivery speed for the high ability of the owner to restrain the contractor pool (3.51, SE 0.13) is greater (p<.05) than the mean log delivery speed for the low ability of the owner to restrain the contractor pool (2.88, SE 1.14).

Univariate results show that owners that have schedule constraints should hold the *contract for energy consultant* position themselves in the project to enable a faster delivery process. Figure F-5 illustrates that mean log delivery speed for the owner as the primary party to hold a contract with the energy consultant (3.85, SE 0.16) is greater (p<.05) than the mean log delivery speed for designers (3.13, SE 0.14) and for the design-builders (3.50, SE 0.23). The mean for the owner as the primary party to hold a contract with the energy consultant does not differ significantly from the mean log delivery speed for design-builders.

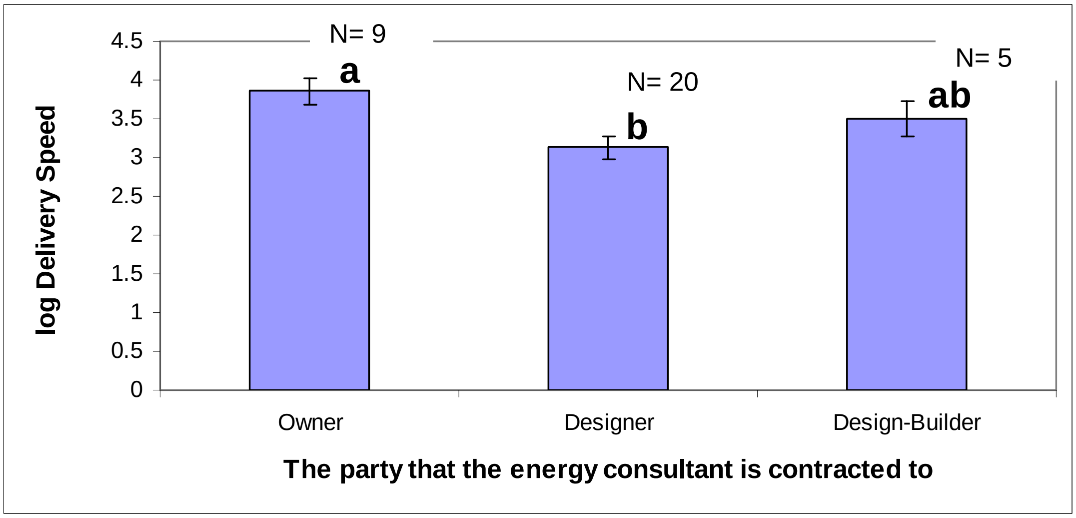


Figure F-5**:** Delivery Speed by Contractual Relations

Descriptive statistics of the significant independent variables for the time metrics and the results of Tukey comparisons for the categorical variables are presented in the time metrics tables below.

Table F-1a: Time Metrics-I / Delivery Speed

Independent Variables	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
logDelSpd											
OwnType	1:Public	15	3.398	0.154	0.598	2.309	2.95	3.484	3.772	4.366	ab
	2:Private	17	3.21	0.158	0.651	2.095	2.645	3.189	3.691	4.49	b
	3:Developer	4	4.0539	0.0902	0.1804	3.8463	3.888	4.0431	4.2305	4.283	a
ProDel	1:CM	15	3.577	0.136	0.528	2.683	3.067	3.623	3.886	4.49	a
	2:DB	8	3.597	0.18	0.51	2.985	3.192	3.528	4.137	4.366	a
	3:DBB	13	3.024	0.194	0.699	2.095	2.553	2.717	3.68	4.327	b
ContRelEnr	1:Owner	9	3.853	0.161	0.484	3.06	3.493	3.7	4.343	4.49	a
	2:Designer	20	3.13	0.143	0.64	2.095	2.597	3.009	3.694	4.366	b
	3:Contractor	0	*	*	*	*	*	*	*	*	
	4:DB	5	3.505	0.224	0.502	2.985	3.093	3.389	3.975	4.283	ab
TimingCont.	0:N/A	8	3.597	0.18	0.51	2.985	3.192	3.528	4.137	4.366	
	1:Predesign	4	3.974	0.197	0.394	3.651	3.659	3.877	4.386	4.49	a
	2:Conceptual	3	3.624	0.45	0.78	2.805	2.805	3.709	4.359	4.359	ab
	3:Schematic	5	3.362	0.379	0.848	2.095	2.578	3.484	4.087	4.327	ab
	4:Design Dev.	3	3.7603	0.076	0.1317	3.6233	3.623	3.7715	3.886	3.886	ab
	5:Const. Docs	3	3.059	0.259	0.448	2.607	2.607	3.067	3.503	3.503	ab
	6:Bidding	10	2.894	0.16	0.506	2.309	2.562	2.7	3.261	4.013	b
TimingCom	1:Predesign	5	3.624	0.226	0.506	2.985	3.187	3.682	4.033	4.366	a
	2:Conceptual	5	2.4208	0.0958	0.2143	2.0955	2.202	2.5347	2.5823	2.594	b
	3:Schematic	8	3.376	0.202	0.572	2.683	2.838	3.283	3.926	4.283	a
	4:Design Dev.	8	3.821	0.19	0.536	3.06	3.308	3.74	4.351	4.49	a
	5:Const. Docs	4	3.812	0.109	0.218	3.503	3.589	3.866	3.981	4.013	a
	6:Bidding	4	3.323	0.183	0.366	2.95	2.979	3.345	3.644	3.651	a
QuanMet	1: Energy	8	3.685	0.225	0.636	2.594	3.176	3.674	4.316	4.359	a
	2: Enr/LPD	6	3.147	0.259	0.633	2.095	2.737	3.124	3.746	3.886	ab
	3: Enr/LPD/PV	5	2.667	0.155	0.347	2.309	2.422	2.571	2.96	3.238	b
	5: Enr/LEED	3	4.029	0.19	0.329	3.709	3.709	4.013	4.366	4.366	a
	6: LEED	3	3.176	0.234	0.405	2.717	2.717	3.329	3.484	3.484	ab
	7: Other	4	3.16	0.26	0.519	2.607	2.701	3.093	3.685	3.846	ab
Qcont.Mech	1: One party	10	3.028	0.207	0.654	2.095	2.588	2.888	3.372	4.283	b
	2: Svrl. parties	7	3.878	0.138	0.366	3.623	3.651	3.682	4.327	4.49	a
	3: Consultant	15	3.345	0.163	0.63	2.309	2.95	3.329	3.846	4.366	ab
Mockup	1:Yes	10	3.696	0.158	0.5	2.95	3.359	3.666	4.006	4.49	a
	2:No	21	3.156	0.138	0.631	2.095	2.6	3.189	3.683	4.327	b
ExpFacSub	1 (None)	4	2.878	0.264	0.527	2.571	2.576	2.638	3.42	3.666	_
	2	2	2.962	0.427	0.604	2.535	*	2.962	*	3.389	
	3	8	3.314	0.204	0.578	2.309	2.978	3.275	3.835	4.073	
	4	13	3.421	0.194	0.699	2.095	2.953	3.329	4.049	4.366	
	5 (Excellent)	7	3.812	0.191	0.504	2.985	3.503	3.709	4.283	4.49	
ExpHPGSub	1 (None)	12	3.155	0.206	0.715	2.309	2.576	2.851	3.745	4.359	_
	2	8	3.171	0.182	0.515	2.095	2.979	3.195	3.632	3.7	
	3	8	3.75	0.141	0.4	3.06	3.533	3.68	4.058	4.366	
	4 (Excellent)	7	3.675	0.25	0.66	2.607	3.238	3.846	4.327	4.49	
Orestrain	1:Low	7	2.885	0.138	0.365	2.309	2.594	2.95	3.238	3.329	b
	2:High	26	3.51	0.131	0.667	2.095	2.94	3.674	4.028	4.49	a

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Table F-1b: Time Metrics-II / Construction Speed & Schedule Growth

Independent Variables	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
LogConstrSpd											
OwnType	1: Public	16	3.705	0.136	0.544	2.782	3.306	3.815	4.042	4.56	ab
	2: Private	17	3.447	0.137	0.565	2.625	2.991	3.423	3.88	4.545	b
	3: Developer	4	4.2645	0.0993	0.1986	4.001	4.0561	4.3169	4.4205	4.4232	a
TimingCont	0: N/A	8	3.766	0.16	0.452	3.216	3.423	3.696	4.26	4.423	ab
	1:Predesign	4	4.159	0.178	0.356	3.682	3.808	4.205	4.464	4.545	a
	2:Conceptual	3	3.859	0.35	0.607	3.233	3.233	3.9	4.444	4.444	ab
	3:Schematic	5	3.632	0.326	0.729	2.625	2.962	3.673	4.28	4.56	ab
	4:Design Dev.	4	4.0193	0.014	0.0281	3.9806	3.991	4.0246	4.0424	4.0476	a
	5:Const. Docs.	3	3.448	0.248	0.429	3.075	3.075	3.352	3.916	3.916	ab
	6:Bidding	10	3.201	0.18	0.57	2.701	2.776	2.894	3.655	4.412	b
TimingCom	1:Predesign	5	3.715	0.202	0.452	3.216	3.319	3.682	4.126	4.394	a
	2:Conceptual	5	2.7441	0.0385	0.0862	2.6246	2.6629	2.7596	2.8177	2.8533	b
	3:Schematic	8	3.615	0.195	0.552	2.881	3.036	3.643	4.112	4.423	a
	4:Design Dev.	9	4.017	0.146	0.438	3.3	3.696	3.981	4.494	4.56	a
	5:Const. Docs.	4	4.094	0.109	0.219	3.916	3.937	4.024	4.321	4.412	a
	6:Bidding	4	3.721	0.225	0.449	3.321	3.329	3.687	4.147	4.188	a
QuanMet	1: Energy	8	3.876	0.216	0.61	2.782	3.434	3.882	4.439	4.56	a
	2: Enr/LPD	7	3.525	0.189	0.499	2.625	3.3	3.544	3.981	4.048	ab
	3: Enr/LPD/PV	5	2.967	0.166	0.37	2.701	2.73	2.853	3.26	3.613	b
	5: Enr/LEED	3	4.236	0.168	0.29	3.9	3.9	4.394	4.412	4.412	a
	6: LEED	3	3.445	0.284	0.492	2.881	2.881	3.673	3.782	3.782	ab
	7: Other	4	3.429	0.204	0.407	3.075	3.11	3.319	3.856	4.001	ab
Qcont.Mech	1: One party	10	3.269	0.19	0.599	2.625	2.776	3.104	3.67	4.423	b
	2: Svrl. parties	7	4.106	0.129	0.342	3.682	3.848	4.022	4.545	4.56	a
	3: Consultant	16	3.631	0.135	0.539	2.701	3.242	3.643	3.996	4.444	ab
Mockup	1:Yes	10	3.909	0.137	0.433	3.216	3.585	4.012	4.24	4.545	a
	2: No	22	3.455	0.126	0.593	2.625	2.874	3.423	3.869	4.56	b
ExpFacSub	1: None	4	3.074	0.26	0.52	2.76	2.765	2.845	3.613	3.848	_
	2	2	3.062	0.361	0.51	2.701	*	3.062	*	3.423	
	3: Average	8	3.556	0.156	0.442	2.853	3.306	3.512	3.956	4.221	
	4	14	3.754	0.159	0.595	2.625	3.336	3.881	4.24	4.56	
	5: Excellent	7	4.039	0.175	0.463	3.216	3.859	3.916	4.423	4.545	
ExpHPGSub	1: None	12	3.355	0.191	0.663	2.701	2.8	3.061	3.982	4.444	_
	2	8	3.435	0.133	0.375	2.625	3.329	3.484	3.68	3.859	
	3: Average	9	4.037	0.112	0.336	3.3	3.908	4.022	4.308	4.412	
	4	7	3.946	0.198	0.524	3.075	3.613	4.001	4.545	4.56	
ExpProSub	1: None	3	2.7892	0.0612	0.106	2.7012	2.7012	2.7596	2.9069	2.9069	_
	2	1	4.2215	*	*	4.2215	*	4.2215	*	4.2215	
	3: Average	7	3.677	0.163	0.432	2.782	3.613	3.682	4.022	4.048	
	4	16	3.655	0.147	0.589	2.625	3.306	3.663	4.148	4.545	
	5: Excellent	9	3.877	0.182	0.547	3.075	3.319	3.9	4.434	4.56	
OTeamRel	1:First time	24	3.65	0.113	0.553	2.625	3.237	3.815	4.026	4.545	ab
	2:Partnering	6	4.097	0.174	0.425	3.613	3.665	4.141	4.473	4.56	a
	3:Repeat	6	3.254	0.235	0.576	2.701	2.745	3.165	3.705	4.188	b
Schedule Growth											
ContRelDMech	1:Owner	1	-9.103	*	*	-9.103	*	-9.1034	*	-9.103	ab
	2:Designer	2	-24.2	17.2	24.3	-41.4	*	-24.2	*	-7	b
	3:Contractor	26	3.22	2.3	11.72	-15.57	-0.5	0	8.23	36.84	a
	4:DB	4	2.23	4.03	8.07	-7.44	-5.58	2.3	9.98	11.78	ab
ContRelElect	1:Owner	1	-9.103	*	*	-9.103	*	-9.1034	*	-9.103	ab
	2:Designer	2	-24.2	17.2	24.3	-41.4	*	-24.2	*	-7	b
	3:Contractor	26	3.22	2.3	11.72	-15.57	-0.5	0	8.23	36.84	a
	4:DB	4	2.23	4.03	8.07	-7.44	-5.58	2.3	9.98	11.78	ab

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Univariate Cost Results

Three dependent variables are used to measure the cost growth metric: cost growth (%), unit cost ($/SF), intensity [($/SF)/Month]. The residual diagnostics required a log transformation for the unit cost and the intensity to satisfy the normality and the equal variances assumptions.

Univariate results show that *owner type* has the potential to affect the cost performance of HPG buildings: Mean cost growth for public type owners (9.24, SE 1.74) is greater ($p<.05$) than mean cost growth for private type of owners (1.76, SE 1.06) and mean cost growth for developers (1.04, SE 2.05).

Timing of contractor's involvement in the design process is found to be an important project delivery attribute with which to influence project cost performance. The mean cost growth for a contractor's involvement in the project at the design development stage (16.82, SE 3.54) is greater ($p<.05$) than the mean cost growth for pre-design (1.59, SE 1.33), conceptual design (1.17, SE 3.06), schematic design (2.55, SE 2.89), construction documents (1.81, SE 1.81), and bidding (5.38, SE 1.64).

The results also show that *the driving force for a project team to build "green"* has a potential to affect the project cost performance. Figure F-6 indicates that mean cost growth for building "green" due to obligations of the client or the state (8.65, SE 2.13) is greater ($p<.05$) than mean cost growth for building "green" as an owner driven factor (2.34, SE 1.12) and mean cost growth for building "green" for less energy use (7.14, SE 3.8). The mean cost growth for building "green" due to obligations of the client or the state does not differ significantly from the mean cost growth for building "green" for less energy use.

Holding collaboration sessions for the achievement of project green goals during the project delivery process and attendance of all project participants in these meetings is important to enable a more integrated environment for project participants. Results show that it is also important to enable less cost growth: Mean cost growth for attendance of all project parties to the green collaboration session except the designer (21.339, SE *) is greater ($p<.05$) than mean cost growth for attendance of all major project parties to the green collaboration session (5.47, SE 0.98), mean cost growth for attendance of all

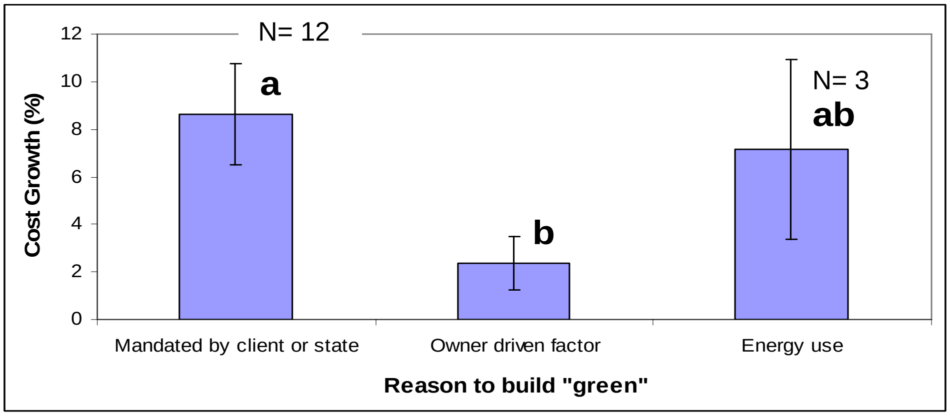


Figure F-6**:** Cost Growth by Primary Reason to Build “Green”

project parties, a commissioning agent to the green collaboration session (0.07, SE 3.04),and mean for attendance of all major project parties to the green collaboration session except for the contractor (0.00, SE 0.00).

Figure F-7 shows that mean cost growth for competitive designer *selection process* (9.37, SE 2.36) is greater (p<.05) than mean cost growth for negotiated designer selection process (2.67, SE 1.28). Similarly, mean cost growth for a competitive contractor selection process (7.81, SE 1.82) is greater (p<.05) than mean cost growth for a negotiated contractor selection process (1.15, SE 1.06). These results indicate that negotiated selection process for designer and the contractor helps enable less cost growth in the project delivery process.

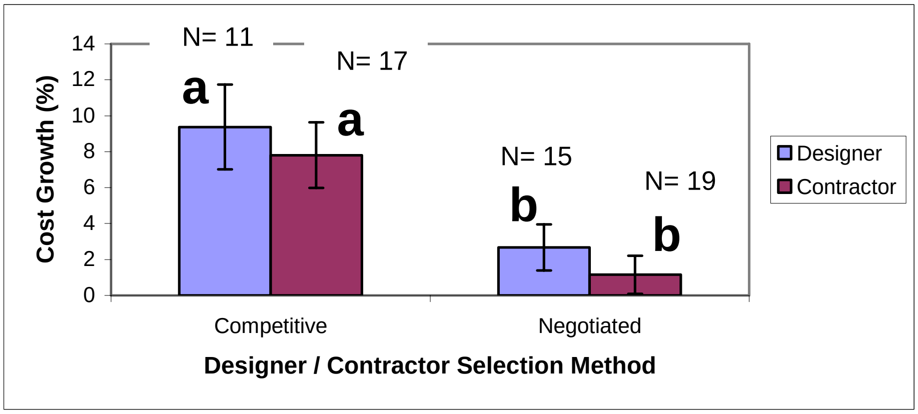


Figure F-7**:** Cost Growth by Designer / Contractor Selection Methods

Experience level of the project owner with the project delivery system type used for the project shows a negative relation with the project cost growth ($p<.05$). In other words, project cost growth decreases as the level of the owner's experience with the project delivery system increases.

The party that holds the contract for the green design coordinator appeared to be important for cost growth in the results. Figure F-8 presents that mean cost growth for the conditions where the green design coordinator is contracted to any other project parties than the owner (7.27, SE 1.7) is greater ($p<.05$) than mean cost growth for owner holding a contract with the green design coordinator (2.30, SE 1.18) and mean cost growth for the conditions where the project does not have a green design coordinator (9.57, SE 6.52). Mean cost growth for the conditions where the green design coordinator is contracted to any other project parties than the owner does not significantly differ than mean cost growth for the conditions where the project does not have a green design coordinator.

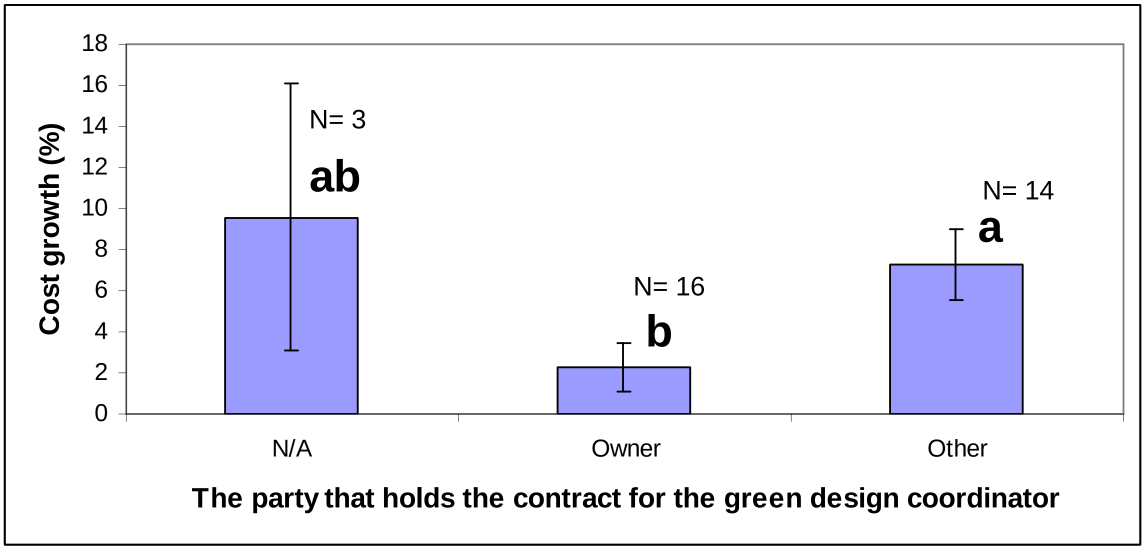


Figure F-8**:** Cost Growth by Contractual Relations

Using various criteria in *major subcontractors' procurement* lead to lower unit project cost for HPG buildings compared to going for the lowest bid. Figure F-9 shows that mean log unit cost for a low-bid procurement method for the selection of mechanical and electrical subcontractors (2.32, SE 0.06) is greater ($p<.05$) than mean log unit cost for qualifications-based selection of mechanical and electrical subcontractors (1.92, SE 0.08), mean log unit cost for sole source selection of mechanical and electrical subcontractors (2.06, SE 0.07), and mean log unit cost for best value selection of mechanical and electrical subcontractors (2.23, SE 0.06). Mean log unit cost for low-bid procurement method for the selection of mechanical and electrical subcontractors did not significantly differ than mean log unit cost for sole source selection and mean log unit cost for best value selection methods.

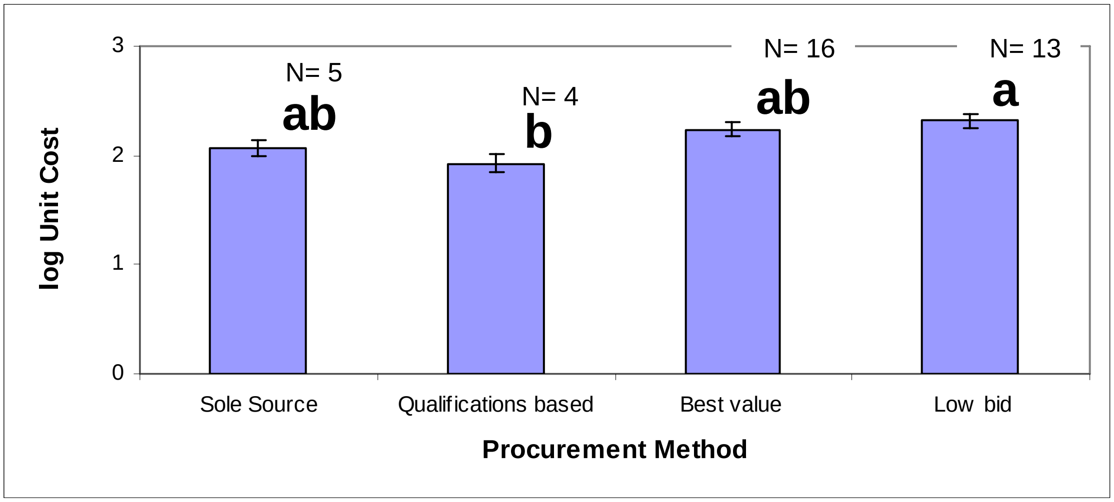


Figure F-9: Unit Cost by Procurement Method for Subcontractors

The results illustrate that *a direct contract between owners and lighting* might contribute to achieving a lower project unit cost. As shown in Figure F-10, mean log unit cost for lighting consultant contracted to designer (2.28, SE 0.05) is greater ($p<.05$) than mean log unit cost for lighting consultant contracted to owner (2.01, SE 0.10), mean log unit cost for lighting consultant contracted to design-builder (2.06, SE 0.06), and mean log unit cost for lighting consultant contracted to contractor (1.80, SE *). Mean log unit cost for lighting consultant contracted to designer does not significantly differ from mean log unit cost for lighting consultant contracted to contractor.

Experience of major subcontractors with the facility type and the project delivery system and owner’s level of experience with HPG buildings, and show a positive relation with the unit cost and intensity in the results ($p< .05$).

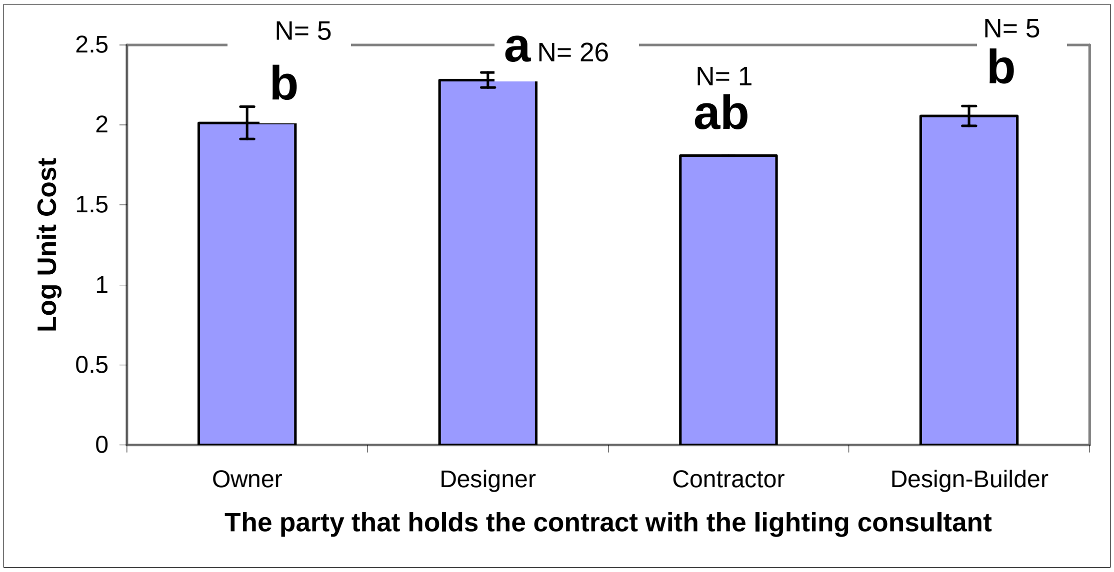


Figure F-10: Unit Cost by Contractual Relations

The *cost plus fee type of contracts* for designers and contractors outperformed all other contract types in the analysis results for intensity. As shown in Figure F-11**,** mean log intensity for cost plus fee contracts with designers (1.23, SE 0.29) is larger (p<.05) than mean log intensity for lump-sum contracts with designers (0.62, SE 0.07), and mean log intensity for guaranteed maximum price for designers (0.62, SE 0.19). Mean log intensity for cost plus fee contracts with designers does not significantly differ from mean log intensity for guaranteed maximum price for designers. Similarly, mean log intensity for cost plus fee contracts with contractors (1.40, SE 0.29) is larger (p<.05) than mean log intensity for lump-sum contracts with contractors (0.70, SE 0.08), and mean log intensity for guaranteed maximum price for contractors (0.50, SE 0.07).

An *owner's experience* with the high-performance green buildings resulted with a positive relation with log intensity (p< .05).

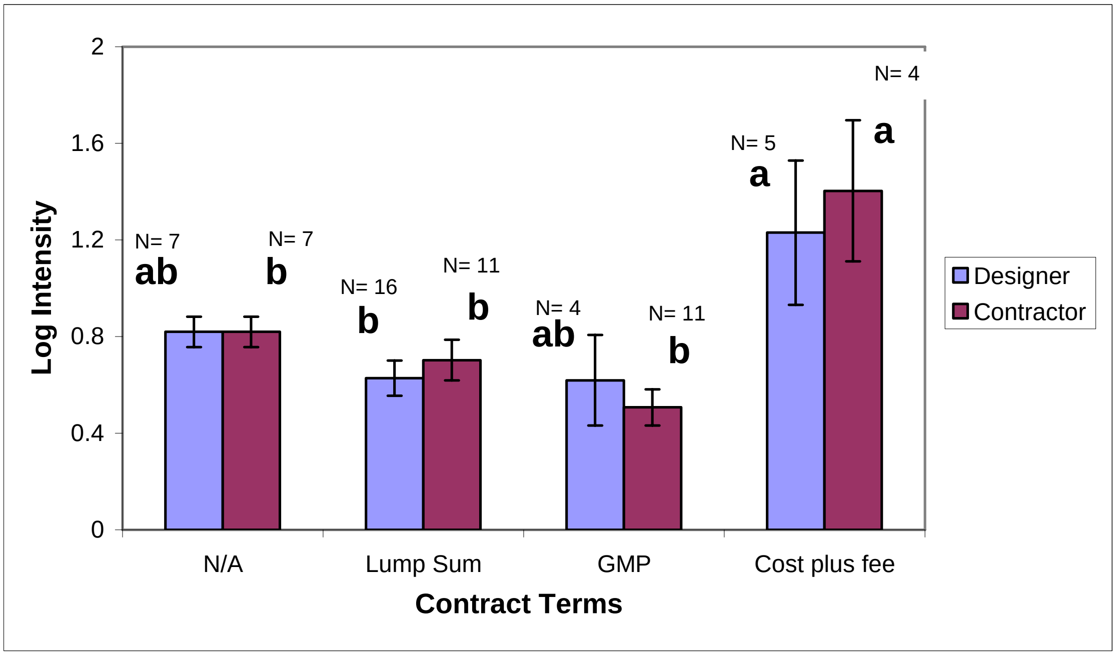


Figure F-11: Intensity by Contractual Terms used for Designer/Contractor

Repeat owner- team relations result in higher project intensity according to the results. Figure F-12 shows that mean log intensity for repeat owner-team projects (1.25, SE 0.22), is larger (p< .05) than mean log intensity for first time projects (0.69, SE 0.06), and mean log intensity for partnering projects (0.52, SE 0.08).

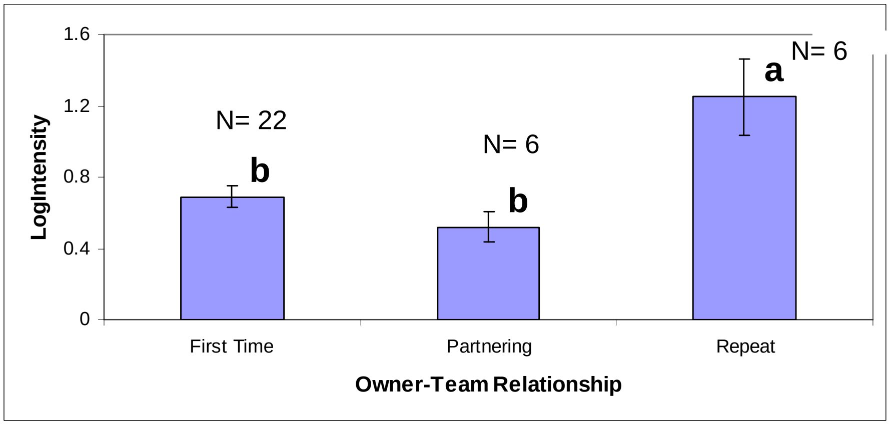


Figure F-12: Intensity by Owner – Team Relation

Descriptive statistics of the significant independent variables for the cost metrics and the results of Tukey comparisons for the categorical variables are presented in the tables below.

Table F-2a: Cost Metrics-I / Cost Growth

Independent Variables	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
Cost Growth											
OwnType	1:Public	15	9.24	1.74	6.73	0	4.26	8.46	12.97	22.02	a
	2:Private	14	1.76	1.06	3.97	-6.94	-0.25	2.97	4.53	7	b
	3:Developer	4	1.04	2.05	4.1	-2.73	-2.05	0	5.16	6.88	b
GrnReason	1:Mandated	12	8.65	2.13	7.39	0.53	4.23	6.11	15.09	22.02	a
	2:Owner driven	18	2.34	1.12	4.73	-6.94	-0.25	2.97	5.73	11.21	b
	3:Energy use	3	7.14	3.8	6.58	0	0	8.46	12.97	12.97	ab
	4:Multiple	0	*	*	*	*	*	*	*	*	
GrnIntro	1: Conceptual	22	2.745	0.872	4.092	-6.936	0	3.45	5.721	11.206	b
	2: Schematic	7	11.1	2.47	6.55	2.67	5.56	9.3	17.24	21.34	a
	3: Design dev.	2	8.7	13.4	18.9	-4.7	*	8.7	*	22	ab
	4: CDs	1	5.0045	*	*	5.0045	*	5.0045	*	5.0045	ab
	5: Bidding	1	6.8799	*	*	6.8799	*	6.8799	*	6.8799	ab
Select Designe	1:Competitive	11	9.37	2.36	7.84	0	2.67	8.46	17.24	22.02	a
	2:Negotiated	15	2.67	1.28	4.96	-6.94	0	3.62	5.56	12.97	b
Select Contrac	1:Competitive	17	7.81	1.82	7.51	-6.94	3.75	6.88	12.09	22.02	a
	2:Negotiated	9	1.15	1.06	3.17	-4.72	-0.5	0	3.93	5.56	b
ContRelGrnDe	0: N/A	3	9.57	6.52	11.29	0	0	6.69	22.02	22.02	
	1:Owner	16	2.3	1.18	4.73	-6.94	0	2.97	5.52	11.21	b
	2:Other	14	7.27	1.7	6.37	-1	3.08	5.46	10.21	21.34	a
TimingContrac	0:Design_Build	7	3.45	1.56	4.14	-2.73	0	4.02	6.67	9.3	b
	1:Predesign	3	1.59	1.33	2.31	0	0	0.53	4.24	4.24	b
	2:Conceptual	3	1.17	3.06	5.3	-4.72	-4.72	2.67	5.56	5.56	b
	3:Schematic	4	2.55	2.89	5.79	-1	-0.75	0	8.4	11.21	b
	4:Design dev.	4	16.82	3.54	7.08	6.69	9.33	19.29	21.85	22.02	a
	5:Const.docs	2	1.81	1.81	2.56	0	*	1.81	*	3.62	b
	6:Bidding	10	5.38	1.64	5.18	-6.94	3.99	5.94	8.5	12.97	b
ColSesAttn	0:N/A	2	8.7	13.4	18.9	-4.7	*	8.7	*	22	ab
	1:All	22	5.468	0.986	4.626	-0.998	1.229	4.633	8.5	17.241	b
	2:All but Cont	2	0	0	0	0	*	0	*	0	b
	3:All but Des	1	21.339	*	*	21.339	*	21.339	*	21.339	a
	4:All and Com	4	0.07	3.04	6.07	-6.94	-5.88	0.28	5.82	6.67	b
ExpProO	1(None)	2	8.6	4.37	6.18	4.23	*	8.6	*	12.97	_
	2	1	3.6219	*	*	3.6219	*	3.6219	*	3.6219	
	3	4	11.17	3.5	6.99	5.41	6.21	8.96	18.33	21.34	
	4	10	7.82	2.32	7.34	-1	1.1	6.79	12.71	22.02	
	5(Excellent)	15	1.4	1.07	4.13	-6.94	0	0.53	4.26	8.46	

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Table F-2b: Cost Metrics-II / Unit Cost

Independent Variables	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
logUnitCost											
ProMetMech	1: Sole S.	5	2.064	0.071	0.159	1.913	1.92	2.0159	2.2324	2.2382	ab
	2: Quals	4	1.9262	0.0834	0.167	1.758	1.771	1.9272	2.0805	2.0923	b
	3: Best value	16	2.2335	0.0623	0.249	1.9	2.018	2.1864	2.4499	2.6284	ab
	5: Low bid	13	2.3157	0.0647	0.233	1.984	2.088	2.3138	2.4852	2.7029	a
ProMetElect	1: Sole S.	5	2.064	0.071	0.159	1.913	1.92	2.0159	2.2324	2.2382	ab
	2: Quals	4	1.9262	0.0834	0.167	1.758	1.771	1.9272	2.0805	2.0923	b
	3: Best value	16	2.2335	0.0623	0.249	1.9	2.018	2.1864	2.4499	2.6284	ab
	5: Low bid	13	2.3157	0.0647	0.233	1.984	2.088	2.3138	2.4852	2.7029	a
ContRelLght	1:Owner	5	2.013	0.101	0.226	1.758	1.842	1.984	2.197	2.375	b
	2:Designer	26	2.281	0.0469	0.239	1.9	2.042	2.2431	2.4793	2.7029	a
	3:Contractor	1	1.8094	*	*	1.809	*	1.8094	*	1.8094	ab
	4:DB	5	2.0564	0.0618	0.138	1.913	1.918	2.072	2.1865	2.2321	b
ExpFacSub	1: Poor	4	2.427	0.126	0.253	2.072	2.168	2.485	2.628	2.666	_
	2	2	2.313	0.39	0.551	1.923	*	2.313	*	2.703	
	3	8	2.2475	0.0982	0.278	1.758	2.007	2.3101	2.4039	2.6247	
	4	16	2.1293	0.0569	0.228	1.809	1.992	2.0686	2.2367	2.6284	
	5:Excellent	6	2.1708	0.0827	0.203	2.004	2.014	2.08	2.3985	2.4678	
ExpHPGO	1: Poor	12	2.0824	0.0556	0.193	1.758	1.939	2.0455	2.2708	2.4065	_
	2	3	2.222	0.161	0.279	1.913	1.913	2.295	2.456	2.456	
	3	11	2.1972	0.0707	0.235	1.926	2.018	2.045	2.3963	2.6247	
	4	8	2.296	0.107	0.304	1.809	2.1	2.235	2.617	2.666	
	5:Excellent	3	2.483	0.137	0.237	2.232	2.232	2.514	2.703	2.703	
ExpHPGDB	1: Poor	7	2.1148	0.0687	0.182	1.924	1.984	2.0191	2.3138	2.4065	_
	2	9	2.1021	0.0802	0.241	1.758	1.92	2.0184	2.3607	2.4564	
	3	9	2.1624	0.0696	0.209	1.9	2.026	2.0923	2.3117	2.5817	
	4	10	2.3984	0.0941	0.298	1.809	2.185	2.4908	2.6377	2.7029	
	5:Excellent	2	2.2351	0.00306	0.004	2.232	*	2.2351	*	2.2382	
ExpProSub	1: None	3	2.6275	0.0578	0.1	2.514	2.514	2.6656	2.7029	2.7029	_
	2	1	1.9263	*	*	1.926	*	1.9263	*	1.9263	
	3	8	2.19	0.104	0.293	1.758	1.929	2.195	2.436	2.625	
	4	17	2.2102	0.0477	0.197	1.924	2.026	2.2321	2.3607	2.6284	
	5:Excellent	8	2.0921	0.0838	0.237	1.809	1.931	2.0379	2.2091	2.5817	

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Table F-2c: Cost Metrics-III / Intensity

Independent	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
logIntensity											
ContractD	0:N/A	7	0.8196	0.063	0.167	0.556	0.6773	0.8465	0.9907	0.9992	ab
	1:Lump Sum	16	0.6274	0.0729	0.292	0.096	0.3871	0.5872	0.88	1.1273	b
	2:GMP	4	0.619	0.187	0.374	0.347	0.352	0.489	1.016	1.151	ab
	3:Cost plus	5	1.23	0.299	0.669	0.246	0.532	1.633	1.725	1.731	a
ContractC	0:N/A	7	0.8196	0.063	0.167	0.556	0.6773	0.8465	0.9907	0.9992	b
	1:Lump Sum	11	0.7023	0.0841	0.279	0.304	0.3797	0.8189	0.8807	1.1273	b
	2:GMP	11	0.5067	0.0744	0.247	0.096	0.3466	0.4218	0.754	0.8962	b
	3:Cost plus	4	1.403	0.292	0.584	0.53	0.806	1.676	1.728	1.731	a
Qcont.Mech	1:One party	10	0.965	0.139	0.441	0.304	0.712	0.864	1.254	1.731	a
	2:Several	7	0.464	0.105	0.279	0.096	0.342	0.37	0.754	0.919	b
	3:Separate	14	0.769	0.101	0.378	0.246	0.5	0.713	0.968	1.719	ab
ExpFacSub	1: None	4	1.353	0.196	0.392	0.919	0.971	1.38	1.707	1.731	_
	2	2	1.359	0.36	0.509	0.999	*	1.359	*	1.719	
	3	8	0.6731	0.0814	0.23	0.347	0.4448	0.6807	0.8799	0.958	
	4	13	0.6033	0.0843	0.304	0.096	0.3606	0.556	0.8576	1.1514	
	5:Excellent	6	0.629	0.107	0.261	0.246	0.339	0.716	0.854	0.878	
ExpHPGO	1: None	12	0.6001	0.0794	0.275	0.096	0.3725	0.5797	0.8697	0.9992	_
	2	3	0.816	0.167	0.289	0.556	0.556	0.763	1.127	1.127	
	3	9	0.6055	0.0904	0.271	0.246	0.3568	0.5979	0.8794	0.958	
	4	8	0.913	0.145	0.41	0.342	0.655	0.858	1.111	1.731	
	5:Excellent	2	1.6761	0.043	0.061	1.633	*	1.6761	*	1.7191	
ExpHPGSub	1: None	11	0.997	0.153	0.506	0.304	0.551	0.919	1.633	1.731	_
	2	8	0.7043	0.0873	0.247	0.347	0.446	0.7481	0.9379	0.9907	
	3	8	0.5152	0.0975	0.276	0.096	0.2769	0.5098	0.7598	0.8781	
	4	7	0.718	0.11	0.292	0.342	0.38	0.754	0.896	1.151	
ExpProSub	1: None	3	1.6944	0.0309	0.053	1.633	1.6331	1.7191	1.7311	1.7311	_
	2	1	0.5979	*	*	0.598	*	0.5979	*	0.5979	
	3	7	0.588	0.141	0.373	0.096	0.347	0.409	0.881	1.127	
	4	15	0.7077	0.0619	0.24	0.246	0.5512	0.754	0.8962	0.9992	
	5:Excellent	8	0.6671	0.0998	0.282	0.342	0.4099	0.5896	0.9006	1.1514	
OTeamRel	1:First Time	22	0.688	0.0596	0.28	0.096	0.5157	0.7513	0.8846	1.1514	b
	2:Partnering	6	0.5202	0.0843	0.206	0.342	0.3454	0.4547	0.7196	0.8465	b
	3:Repeat	6	1.249	0.217	0.532	0.422	0.848	1.316	1.722	1.731	a

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Univariate Quality Results

Quality is evaluated using three metrics in this study: turnover quality, system quality and overall quality. All these metrics are calculated using a Likert scale, where higher numbers represent better quality as well as higher owner satisfaction. The following points are available for each metric in total for turnover quality, system quality and overall quality respectively: 15, 15, and 20.

The univariate results showed a negative relation between the importance of the *quality criteria in the request for proposals* and the turnover and system qualities (p<

.05). This result contradicts the researcher's expectation of acquiring a positive relationship between these variables. However, it also indicates the difficulty to satisfy owners with high quality expectations.

The projects that did not have a *green design coordinator* presented a lower turnover quality: Mean turnover quality for projects with green design coordinators (3, SE *), is lower (p< .05) than mean turnover quality for projects with green design coordinators contracted to owners (9.89, SE 0.46) and other project parties (9.07, SE 0.58). The *subcontractor's educated* with green construction method resulted with higher mean turnover quality (10.14, SE 0.43) than non- educated ones (8.43, SE 0.53) (p< .05). *Quality of workmanship* for the mechanical systems' construction and *the owners' ability to define the scope* of projects are positively correlated to the turnover quality (p< .05).

Lastly, repeat *owner-team relations* appeared to be an important indicator of the turnover quality performance. Figure F-13 shows that mean turnover quality for the repeat owner-team relations (11.17, SE 0.91), is higher than (p< .05) mean turnover quality for first time owner-team experience in the project (8.7, SE 0.54), and mean for partnering (9.14, SE 0.55). Mean turnover quality for the repeat owner-team relations does not differ significantly from mean turnover quality for partnering relations between the owner and the project team.

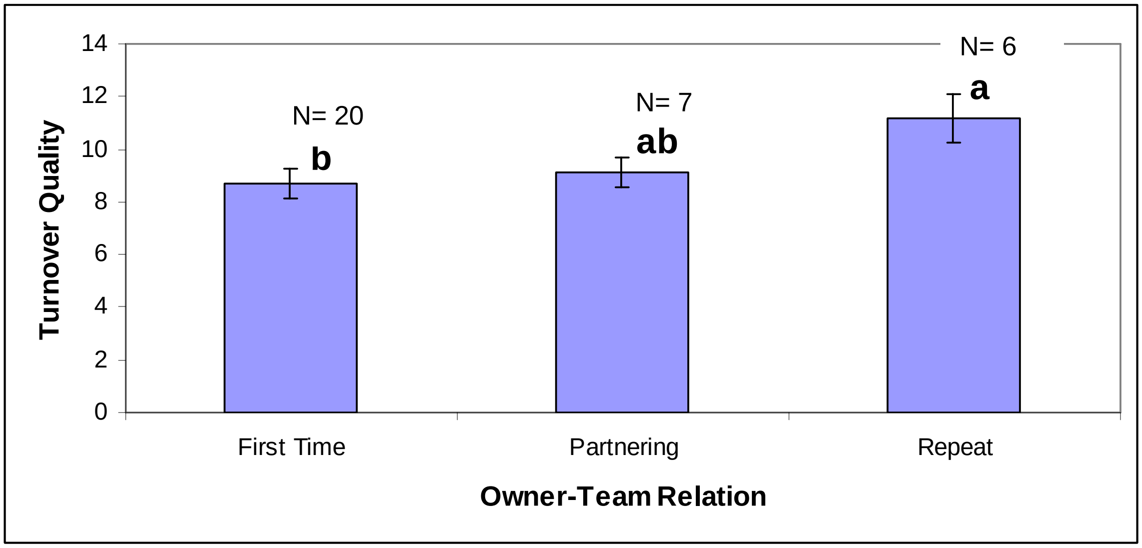


Figure F-13: Turnover Quality by Owner-Team Relation

Early *involvement of mechanical and electrical subcontractors' involvement* in the design process also appeared to be important for achieving higher system quality. Early *involvement of lighting consultants* in the project delivery process for HPG buildings resulted to be important for project system and overall quality.

Low bid *procurement method* for the mechanical and electrical subcontractors selection resulted with the lowest mean system quality. Mean system quality for low bid procurement method used in the selection of these subcontractors (10.46, SE 0.58) is lower (p< .05) than mean system quality for sole source selection (13.5, SE 0.5), qualifications based selection (13.25, SE 0.25), and for best value source selection (11.57, SE 0.46). Mean system quality for low-bid does not differ significantly from mean system quality for best value source selection (see Figure F-14).

Quality of workmanship with the envelope construction and *experience of the owner* with the project delivery method used showed positive correlations with the system quality in the univariate results (p <.05).

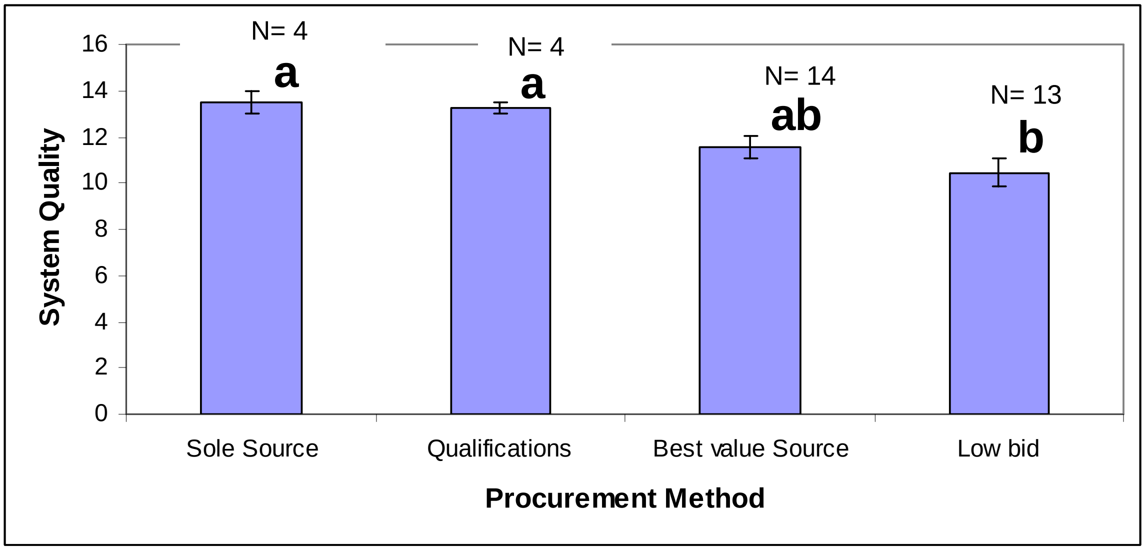


Figure F-14**:** System Quality by Procurement Method for Subcontractors

Figure F-15 illustrates that mean system quality for the projects where *energy simulations* were utilized early in the process (12.88, SE 0.66) outperformed (p< .05) mean system quality for projects that integrated energy simulations later in the process (9.4, SE 1.21).

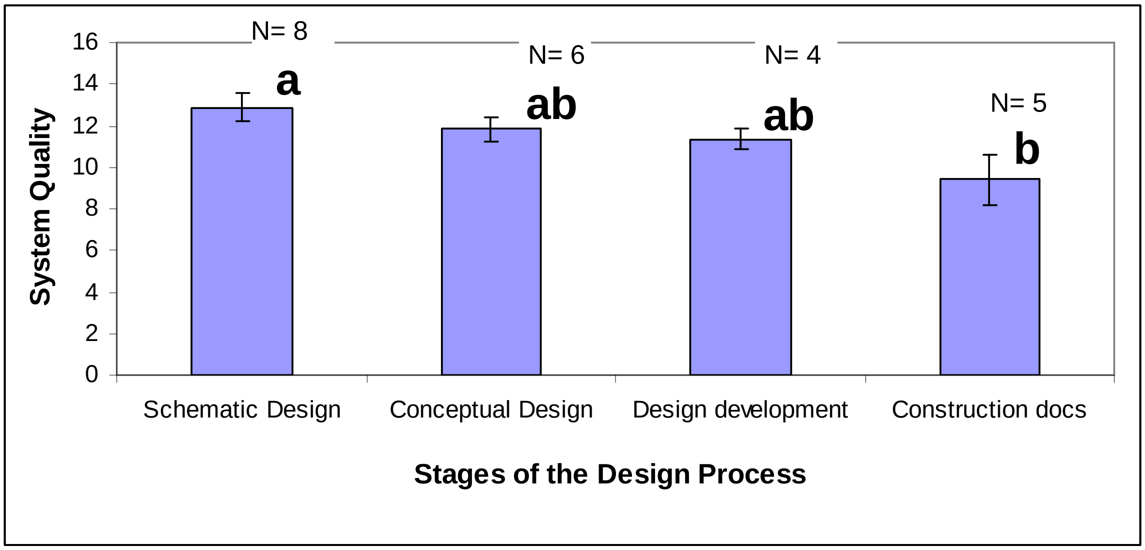


Figure F-15**:** System Quality by Timing of Energy Simulations Use

The results pointed out that bringing a separate consultant on board in the construction process for quality control of the mechanical systems lead to a higher (p< .05) mean overall quality value (18.31, SE 0.35), than mean overall quality for projects with only one party such as the field team doing the mechanical system quality controls (16.56, SE 0.29). Another construction application, the use of building envelope mock-ups, also help generates higher overall quality (p< .05).

The design and construction teams' *level of experience* with the high-performance green buildings, *team chemistry,* and *owner's capacity,* showed positive relations with the overall quality metric.

An owner's level of satisfaction with the cost performance of the buildings (despite the growth, if any) did not show any significant relation with the unit cost of the project; therefore, is not found to be a meaningful metric for HPG project delivery. Descriptive statistics of the significant independent variables for the cost metrics and the results of Tukey comparisons for the categorical variables are presented in the tables below.

Table F-3a: Quality Metrics-I / Turnover Quality

Independent variable	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
TurnOvrQ											
RFP Qua	1: Not Imp	2	10	2	2.83	8	*	10	*	12	_
	2: Somewh	2	9	0	0	9	*	9	*	9	
	3: Importa	14	10.786	0.482	1.805	8	9	11	12	14	
	4: Very im	16	8	0.548	2.191	3	6	9	10	11	
	*	0	*	*	*	*	*	*	*	*	
ContRelG	N/A	1	3	*	*	3	*	3	*	3	b
	Owner	17	9.765	0.466	1.921	7	8.5	9	11.5	14	a
	Architect	10	8.8	0.68	2.15	6	6	9	10.25	12	a
	DB	6	10	1.03	2.53	6	8.25	10	12.25	13	a
ConRelGrnDes	N/A	1	3	*	*	3	*	3	*	3	b
	Owner	18	9.889	0.457	1.937	7	8.75	9.5	12	14	a
	Other	15	9.067	0.581	2.251	6	6	9	11	13	a
SubsEd	1:Yes	22	10.136	0.428	2.007	6	9	10	12	14	a
	2:No	7	8.429	0.528	1.397	6	7	9	9	10	b
QWorkMech	3	5	8	0.632	1.414	6	6.5	9	9	9	_
	4	12	9.083	0.583	2.021	6	7.5	9	10.75	12	
	5:Excellen	13	10.308	0.444	1.601	8	9	10	12	13	
Oscope	2	1	9	*	*	9	*	9	*	9	_
	3	8	8.125	0.549	1.553	6	6.25	9	9	10	
	4	12	8.75	0.799	2.768	3	6.25	9	11	12	
	5:Excellen	12	10.5	0.557	1.931	8	9	10	12	14	
	*	1	12	*	*	12	*	12	*	12	
OTeamRel	1:First Tim	20	8.7	0.534	2.386	3	6.25	9	10	13	b
	2:Partnerir	7	9.143	0.553	1.464	7	8	9	11	11	ab
	3:Repeat	6	11.167	0.91	2.229	8	8.75	12	12.5	14	a

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Table F-3b: Quality Metrics-II / System Quality

Independent Variables	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
SystQ											
ProMetMech	1:Sole Sour	4	13.5	0.5	1	12	12.5	14	14	14	a
	2:Qualificati	4	13.25	0.25	0.5	13	13	13	13.8	14	a
	3:Best value	14	11.57	0.465	1.742	9	10	12	12.3	15	ab
	5:Low bid	13	10.46	0.584	2.106	7	9	10	12.5	14	b
ProMetElect	Sole Source	4	13.5	0.5	1	12	12.5	14	14	14	a
	Qualification	4	13.25	0.25	0.5	13	13	13	13.8	14	a
	Best value S	14	11.57	0.465	1.742	9	10	12	12.3	15	ab
	Low bid	13	10.46	0.584	2.106	7	9	10	12.5	14	b
RFP Qua	1: not Impor	2	13.5	1.5	2.12	12	*	13.5	*	15	_
	2: somewha	2	12	2	2.83	10	*	12	*	14	
	3: important	14	12.21	0.505	1.888	9	10.8	13	14	14	
	4: very impo	17	10.77	0.45	1.855	7	9	11	12	13	
IncPen	N/A	21	11.95	0.348	1.596	9	11	12	13	15	a
	Yes	6	9.667	0.955	2.338	7	8.5	9	11	14	b
	Multiple	8	12	0.779	2.204	8	10.3	12.5	14	14	a
TimingMech	Predesign	5	13.6	0.51	1.14	12	12.5	14	14.5	15	a
	Conceptual	6	12	0.365	0.894	11	11	12	13	13	ab
	Schematic	2	11.5	2.5	3.54	9	*	11.5	*	14	ab
	Design deve	3	13	0.577	1	12	12	13	14	14	ab
	Constructio	5	11.8	0.86	1.924	9	10	12	13.5	14	ab
	Bidding	14	10.29	0.518	1.939	7	9	10	12	14	b
TimingElect	Predesign	5	13.6	0.51	1.14	12	12.5	14	14.5	15	a
	Conceptual	5	11.8	0.374	0.837	11	11	12	12.5	13	ab
	Schematic	2	11.5	2.5	3.54	9	*	11.5	*	14	ab
	Design deve	3	13	0.577	1	12	12	13	14	14	ab
	Constructio	6	12	0.73	1.789	9	10.5	12.5	13.3	14	ab
	Bidding	14	10.29	0.518	1.939	7	9	10	12	14	b
TimingLghtng	N/A	2	13.5	0.5	0.707	13	*	13.5	*	14	a
	Predesign	6	13.33	0.494	1.211	12	12	13.5	14.3	15	a
	Conceptual	15	11.6	0.445	1.724	8	11	12	13	14	b
	Schematic	9	10.22	0.703	2.108	7	9	10	12	14	ab
	Design deve	1	10	*	*	10	*	10	*	10	ab
	Bidding	1	9	*	*	9	*	9	*	9	ab
StgEnrgySim	2: Schemati	8	12.88	0.666	1.885	9	12	13.5	14	15	a
	3: Conceptu	6	11.83	0.601	1.472	10	10.8	11.5	13.3	14	ab
	4: Design de	11	11.36	0.491	1.629	9	10	12	13	13	ab
	5: Construc	5	9.4	1.21	2.7	7	7.5	9	11.5	14	b
QWorkEnvlp	3	2	9.5	1.5	2.12	8	*	9.5	*	11	_
	4	9	10.67	0.601	1.803	9	9	10	13	13	
	5:Excellent	21	12.1	0.447	2.047	7	11	12	14	15	
ExpProO	1: None	3	9.333	0.882	1.528	8	8	9	11	11	_
	2	0	*	*	*	*	*	*	*	*	
	3	5	12.2	0.8	1.789	10	10.5	12	14	14	
	4	10	10.9	0.674	2.132	7	9	11.5	12.3	14	
	5:Excellent	16	12.25	0.461	1.844	9	10.5	13	13.8	15	

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Table F-3c: Quality Metrics-III / Overall Quality

Independent Variables	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
OverallQ											
TimingLghtng	N/A	2	19.5	0.5	0.707	19	*	19.5	*	20	a
	Predesign	6	18.167	0.654	1.602	16	16.75	18	20	20	a
	Conceptua	15	17.867	0.35	1.356	16	16	18	19	20	a
	Schematic	9	18.444	0.556	1.667	16	17	18	20	20	a
	Design Dev	1	13	*	*	13	*	13	*	13	b
	Bidding	1	17	*	*	17	*	17	*	17	ab
Qcont.Mech	1:One party	9	16.556	0.294	0.882	16	16	16	17.5	18	b
	2:Several p	6	18.17	1.08	2.64	13	16.75	19	20	20	ab
	3:Includes	16	18.313	0.35	1.401	16	17.25	18	20	20	a
Mockup	1:Yes	9	18.778	0.434	1.302	16	18	19	20	20	a
	2:No	20	17.2	0.381	1.704	13	16	17	18	20	b
ExpHPGDB	1 (None)	8	18.5	0.535	1.512	16	17.25	18.5	20	20	–
	2	8	16.5	0.655	1.852	13	16	16	18	19	
	3	8	18.375	0.498	1.408	16	17.25	18.5	19.75	20	
	4	8	18.25	0.491	1.389	16	17.25	18	19.75	20	
	5 (Excellen	2	19.5	0.5	0.707	19	*	19.5	*	20	
TeamChem	1 (Poor)	1	13	*	*	13	*	13	*	13	–
	2	5	17	0.775	1.732	16	16	16	18.5	20	
	3	19	18.211	0.338	1.475	16	17	18	20	20	
	5 (Excellen	9	18.667	0.333	1	17	18	19	19.5	20	
Ocap	1 (Poor)	1	13	*	*	13	*	13	*	13	–
	2	5	17.2	0.8	1.789	16	16	16	19	20	
	3	11	18.455	0.434	1.44	16	18	19	20	20	
	5 (Excellen	17	18.235	0.327	1.348	16	17	18	19.5	20	
OComPer	2	2	14.5	1.5	2.12	13	*	14.5	*	16	–
	3	2	18.5	0.5	0.707	18	*	18.5	*	19	
	4	16	18	0.398	1.592	16	16	18	19.75	20	
	5 (Excellen	12	18.417	0.379	1.311	16	17.25	18.5	19.75	20	

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Univariate High-performance Green Results

Three dependent variables are used in this research to define the level of high-performance green in projects: energy, indoor environmental quality, and green rates. These variables are represented by the percentage of achieved points out of possible points using the LEED^{TM} scoring system.

The results show that importance level of *quality defined in request for proposals* is negatively correlated to the energy and green performance of the projects ($p < .05$). It is important to widen the criteria to affect the results of this analysis in future research to understand the reasons of such a relationship.

Similarly, the *envelope mock-up* construction variable resulted with unexpected mean energy rate and green rate values. For example, mean energy rate for projects that included envelope mock-ups (33.69, SE 5.83) is lower (p< .05) than mean energy rate for projects that did not include any (59.6, SE 4.26). This outcome strengthens the interpretations made by the researcher for explaining the relations between the previous variable and the energy rate: Project teams focusing on more complicated envelope systems for satisfying owners' quality criteria where these envelope systems might not be highly insulated for achieving high energy performance, yet might need mock-ups for constructability reasons.

The projects that did not include a condition in their *contracts regarding "green" achievement criteria* resulted with lower mean energy rate than the ones that did. Mean energy rate for these projects (38.97, SE 8.61) is significantly different (p< .05) than the mean energy rate for projects that included "green" achievement criteria in their contracts with design-builders (63.24, SE 8.52). This shows that both design and build teams' commitment through their contracts to "green" objectives of projects is necessary for the achievement of those.

The projects that did not involve an *indoor environmental consultant* in their process ended up with the lowest mean energy rate (p< .05). Earlier involvement of an indoor environmental consultant in the process generated higher mean energy rate values.

The completion rate of the construction documents (CDs) at the time of the envelope and mechanical systems' construction indicated a negative relation with the energy and green rate. Even though this trend can not be fully explained by any specific reasons, such a relation might be influenced by the project delivery system effects, which presented a potential significance in the results with a p-value lower than .2 for energy rate achievement. Additionally, the outlier project data generating the negative relation between the CDs completion rate and green rate is a design-build project. Design-build projects have lower percentages of CDs completion at the time of construction due to the advantage of having high levels of integration between project parties during the design process. The level of team integration is also a potential variable which can positively affect the energy performance of buildings. These conflicting effects may have resulted with the negative relation between CDs completion rate and energy rate achieved, however an extended investigation is needed regarding these variables to make meaningful interpretations.

Quality of the workmanship for the envelope and the mechanical systems resulted with a positive relation with the energy rates achieved in projects ($p < .05$). Importance level of technical aspects spelled out in request for proposals also showed positive relationship with the indoor environmental quality rate achieved ($p < .05$).

Figure F-16 shows that *contractual relations of the mechanical and the electrical subcontractors* with the major project actors (e.g. owner, designer, and contractor) resulted with different mean green rates: Mean green rate for a project where the mechanical and electrical subcontractors were contracted to the owner (89.96, SE *) is higher ($p < .05$) than mean energy rate of other projects (around 55.00).

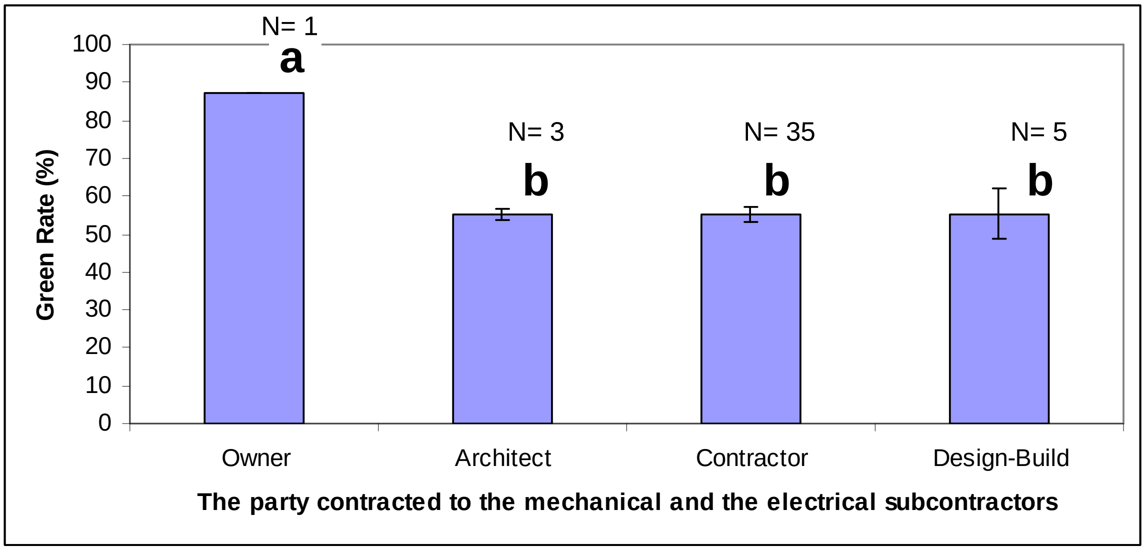


Figure F-16**:** Green Rate by Contractual Relations

Table F-4a: HPG Metrics-I / Energy Rate

Independent Variables	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max.	Tukey
EnergyRate											
RFP Qua	1:Not imp.	2	73.5	20.6	29.1	52.9	*	73.5	*	94.1	_
	2:Somewhat	2	52.9	17.6	25	35.3	*	52.9	*	70.6	
	3:Important	16	59.16	4.48	17.9	29.41	48.53	52.94	76.47	88.24	
	4:Very Imp.	19	38.7	4.68	20.41	5.88	29.41	35.29	47.06	82.35	
Green Cont	1:None	8	38.97	8.61	24.34	5.88	16.18	41.18	51.47	82.35	b
	2:Architect	18	53.89	4.01	17.02	29.41	44.12	52.94	58.82	88.24	ab
	3:Contractor	3	31.4	13.7	23.8	5.9	5.9	35.3	52.9	52.9	ab
	4:DB	8	63.24	8.52	24.1	35.29	36.76	64.71	86.76	94.12	a
	5:Multiple	2	32.35	2.94	4.16	29.41	*	32.35	*	35.29	ab
TimingIAQ	0: N/A	10	49.36	6.45	20.39	5.88	38.24	52.94	61.76	76.47	b
	1:Predesign	6	69.61	8.78	21.51	41.18	50	70.59	89.71	94.12	a
	2:Conceptual	13	39.37	5.63	20.29	5.88	32.35	35.29	50	88.24	ab
	5:CDs	5	52.9	10.4	23.2	29.4	32.4	52.9	73.5	88.2	ab
	6:Bidding	2	32.35	2.94	4.16	29.41	*	32.35	*	35.29	ab
CDPerctg	0	1	94.118	*	*	94.118	*	94.118	*	94.118	_
	30%	1	82.353	*	*	82.353	*	82.353	*	82.353	
	75%	3	50.98	7.84	13.58	35.29	35.29	58.82	58.82	58.82	
	80%	2	20.59	8.82	12.48	11.76	*	20.59	*	29.41	
	85%	2	67.6	20.6	29.1	47.1	*	67.6	*	88.2	
	90%	1	35.294	*	*	35.294	*	35.294	*	35.294	
	100%	23	48.32	4.6	22.07	5.88	35.29	52.94	58.33	88.24	
QWorkEnvlp	3 (Average)	3	46.9	8.88	15.38	29.41	29.41	52.94	58.33	58.33	_
	4	11	36.36	6.86	22.75	5.88	11.76	35.29	52.94	76.47	
	5 (Excellent)	22	58.56	4.32	20.25	29.41	45.59	52.94	82.35	94.12	
QWorkMech	3 (Average)	6	33.3	12.3	30.1	5.9	5.9	32.4	48.5	88.2	_
	4	14	50.39	5.33	19.93	11.76	33.82	52.94	61.76	82.35	
	5 (Excellent)	15	58.04	5.16	19.99	35.29	47.06	52.94	82.35	94.12	
Mockup	1:Yes	11	33.69	5.83	19.35	5.88	11.76	35.29	47.06	58.82	b
	2:No	22	59.6	4.26	19.99	35.29	44.12	52.94	82.35	94.12	a
IEQRate											
RFPTech	1: not Importar	3	57.78	2.22	3.85	53.33	53.33	60	60	60	_
	2: somewhat ir	3	64.44	8.01	13.88	53.33	53.33	60	80	80	
	3: important,	24	64.37	3.22	15.77	33.33	53.33	66.67	78.33	93.33	
	4: very importa	9	76.3	4.73	14.19	60	63.33	73.33	86.67	100	
	*	1	86.667	*	*	86.667	*	86.667	*	86.667	
ExpFacSub	1 (None)	4	73.33	3.85	7.7	66.67	66.67	73.33	80	80	_
	2	2	70	10	14.1	60	*	70	*	80	
	3	8	73.93	2.96	8.36	66.67	66.67	72.38	83.33	86.67	
	4	16	61.67	3.31	13.22	33.33	53.33	60	71.67	86.67	
	5 (Excellent)	7	56.19	6.64	17.58	40	40	53.33	73.33	86.67	

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Table F-4b: HPG Metrics-II / Green Rate

Independent Variables	Levels	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max	Tukey
GreenRate											
RFP Qua	1: Not Imp.	2	67.4	19.6	27.7	47.8	*	67.4	*	87	_
	2: Somewhat	2	56.52	2.9	4.1	53.62	*	56.52	*	59.42	
	3: Important	16	58.49	2.75	11.01	37.68	53.62	57.97	67.03	76.81	
	4: Very imp.	19	52.4	2.34	10.19	37.68	43.48	50.72	59.42	75.36	
	*	1	62.319	*	*	62.319	*	62.319	*	62.319	
ContRelMech	1:Owner	1	86.957	*	*	86.957	*	86.957	*	86.957	a
	2:Architect	3	55.07	1.45	2.51	53.62	53.62	53.62	57.97	57.97	b
	3:Contractor	31	55.25	1.87	10.39	37.68	47.83	56.52	62.32	76.81	b
	4:DB	5	55.36	6.66	14.9	37.68	42.75	50.72	70.29	75.36	b
ContRelElect	1:Owner	1	86.957	*	*	86.957	*	86.957	*	86.957	a
	2:Architect	3	55.07	1.45	2.51	53.62	53.62	53.62	57.97	57.97	b
	3:Contractor	31	55.25	1.87	10.39	37.68	47.83	56.52	62.32	76.81	b
	4:Design-Buil	5	55.36	6.66	14.9	37.68	42.75	50.72	70.29	75.36	b
StgLightSim	*	7	57.51	2.68	7.09	47.83	50.72	57.97	62.32	69.23	
	1: Not used	2	49.3	11.6	16.4	37.7	*	49.3	*	60.9	ab
	2: Schematic	7	59.21	5.71	15.09	39.13	40.58	60.87	75.36	76.81	ab
	3: Conceptua	5	68.7	6.24	13.96	49.28	56.52	68.12	81.16	86.96	a
	4: Design Dev	17	52.43	1.78	7.32	39.13	47.83	53.62	58.7	62.32	b
	5: Const. doc	2	45.65	7.97	11.27	37.68	*	45.65	*	53.62	ab
CDPerctg	0	1	86.957	*	*	86.957	*	86.957	*	86.957	_
	30%	1	60.87	*	*	60.87	*	60.87	*	60.87	
	75%	3	54.1	10.9	18.9	39.1	39.1	47.8	75.4	75.4	
	80%	2	43.48	4.35	6.15	39.13	*	43.48	*	47.83	
	85%	2	68.84	6.52	9.22	62.32	*	68.84	*	75.36	
	90%	1	60.87	*	*	60.87	*	60.87	*	60.87	
	100%	23	55.06	2.17	10.39	37.68	47.83	56.52	62.32	76.81	
	*	7	54.24	2.19	5.79	47.83	47.83	53.62	59.42	62.32	
Mockup	Yes	11	48.88	3.71	12.3	37.68	39.13	43.48	56.52	75.36	b
	No	22	60.72	2.22	10.42	39.13	53.62	59.42	65.94	86.96	a
	*	7	52.59	2.16	5.72	47.83	47.83	50.72	57.97	62.32	

_: ANOVA and Tukey comparison is not applicable due to types of variables being continious.

Appendix G

Multivariate Results

1) General Linear Model: CostGrw versus OwnType, TimingC, ...

```
Factor      Type   Levels  Values
OwnType     fixed       3  1, 2, 3
TimingC     fixed       7  0, 1, 2, 3, 4, 5, 6
ContPool    fixed       3  1, 2, 4
Complexity  fixed       3  3, 4, 5


Analysis of Variance for CostGrw, using Adjusted SS for Tests

Source      DF   Seq SS  Adj SS  Adj MS     F      P
OwnType      2   479.03  175.57   87.79  3.90  0.037
TimingC      6   339.31  396.95   66.16  2.94  0.032
ContPool     2     2.10    1.37    0.68  0.03  0.970
Complexity   2    97.70   97.70   48.85  2.17  0.141
Error       20   450.58  450.58   22.53
Total       32  1368.72

S = 4.74647   R-Sq = 67.08%   R-Sq(adj) = 47.33%

Term          Coef  SE Coef      T      P
Constant     6.104    2.304   2.65  0.015
OwnType
1            3.901    1.512   2.58  0.018
2           -3.924    1.984  -1.98  0.062
TimingC
0            0.474    1.907   0.25  0.806
1           -4.873    2.863  -1.70  0.104
2           -1.025    3.007  -0.34  0.737
3           -4.800    2.563  -1.87  0.076
4            9.380    2.670   3.51  0.002
5            1.332    3.442   0.39  0.703
ContPool
1            0.500    2.045   0.24  0.809
2            0.074    2.511   0.03  0.977
Complexity
3            4.403    2.998   1.47  0.157
4           -0.484    1.750  -0.28  0.785


Least Squares Means for CostGrw
OwnType       Mean  SE Mean   Tukey Comparison Notations
1           10.005    2.676   a
2            2.180    2.449   b
3            6.127    3.590   ab
TimingC
0            6.578    3.049   ab
1            1.231    3.258   b
2            5.079    4.235   ab
3            1.304    3.061   b
4           15.484    3.531   a
5            7.436    4.656   ab
6            5.616    2.269   b
```

2) General Linear Model: logconspd versus OwnType, TimingDCom

```
Factor      Type   Levels  Values
OwnType     fixed       3  1, 2, 3
TimingDCom  fixed       6  1, 2, 3, 4, 5, 6


Analysis of Variance for logconspd, using Adjusted SS for Tests

Source      DF   Seq SS  Adj SS  Adj MS      F      P
Size         1   5.7835  1.9686  1.9686  25.73  0.000 (covariate)
OwnType      2   1.0062  0.7342  0.3671   4.80  0.017
TimingCom    5   2.6133  2.6133  0.5227   6.83  0.000
Error       26   1.9892  1.9892  0.0765
Total       34  11.3921


S = 0.276600   R-Sq = 82.54%   R-Sq(adj) = 77.17%


Term            Coef  SE Coef      T      P
Constant     3.57079  0.07497  47.63  0.000
Size        0.000001  0.000000      *      *
OwnType
1           -0.07415  0.07731  -0.96  0.346
2           -0.24991  0.08223  -3.04  0.005
TimingDCom
1             0.1865   0.1193   1.56  0.130
2            -0.6526   0.1189  -5.49  0.000
3           -0.05970  0.09863  -0.61  0.550
4             0.2386   0.1008   2.37  0.026
5             0.1312   0.1401   0.94  0.358


Means for Covariates

Covariate    Mean   StDev
Size       221819  316027


Least Squares Means for logconspd

OwnType      Mean  SE Mean Tukey Comparison Notation
1           3.691  0.07447       ab
2           3.515  0.07722       b
3           4.089  0.16371       a
TimingCom
1           3.952  0.14149       a
2           3.112  0.13968       b
3           3.705  0.10027       a
4           4.004  0.11796       a
5           3.896  0.14236       a
6           3.921  0.15189       a
```

3) General Linear Model: logDelSpd versus OwnType, TimingC, ...

```
Factor       Type   Levels  Values
OwnType      fixed       3  1, 2, 3
TimingC      fixed       7  0, 1, 2, 3, 4, 5, 6
ArchIntFin   fixed       5  1, 2, 3, 4, 5
Site         fixed       3  1, 2, 3


Analysis of Variance for logDelSpd, using Adjusted SS for Tests

Source       DF    Seq SS   Adj SS   Adj MS      F      P
Size          1   5.89000  1.09054  1.09054  19.44  0.001 (covariate)
OwnType       2   0.77696  0.94996  0.47498   8.47  0.005
TimingC       6   2.58282  2.28574  0.38096   6.79  0.003
ArchIntFin    4   0.54775  0.45853  0.11463   2.04  0.152
Site          2   0.14073  0.14073  0.07036   1.25  0.320
Error        12   0.67313  0.67313  0.05609
Total        27  10.61138


S = 0.236841   R-Sq = 93.66%   R-Sq(adj) = 85.73%


Term             Coef   SE Coef      T      P
Constant       3.3210    0.1337  24.84  0.000
Size         0.000001  0.000000      *      *
OwnType
1             0.00967   0.08772   0.11  0.914
2             -0.4395    0.1108  -3.97  0.002
TimingC
0              0.0903    0.1629   0.55  0.590
1              0.0897    0.1462   0.61  0.551
2              0.6071    0.1762   3.44  0.005
3             -0.5154    0.1312  -3.93  0.002
4             -0.1016    0.1734  -0.59  0.569
5              0.3379    0.2628   1.29  0.223

Means for Covariates

Covariate    Mean   StDev
Size       218624  339555


Least Squares Means for logDelSpd

OwnType      Mean  SE Mean Tukey Comparison Notation
1           3.529   0.1084      a
2           3.080   0.1121      b
3           3.949   0.2575      a
TimingC
0           3.610   0.2425      ab
1           3.609   0.1899      a
2           4.127   0.2138      a
3           3.004   0.1576      b
4           3.418   0.2234      ab
5           3.857   0.2702      ab
6           3.012   0.1699      b
```

4) General Linear Model: EnergyRt versus Mockup

```
Factor  Type   Levels  Values
Mockup  fixed       2  1, 2


Analysis of Variance for EnergyRt, using Adjusted SS for Tests

Source    DF   Seq SS  Adj SS  Adj MS      F      P
CDPerctg   1   2395.0  1918.1  1918.1   5.63  0.025 (covariate)
Mockup     1   4875.2  4875.2  4875.2  14.31  0.001
Error     28   9537.1  9537.1   340.6
Total     30  16807.4


S = 18.4557   R-Sq = 43.26%   R-Sq(adj) = 39.20%


Term          Coef  SE Coef      T      P
Constant     80.22    14.25   5.63  0.000
CDPerctg   -0.3619   0.1525  -2.37  0.025
Mockup
1          -13.139    3.473  -3.78  0.001


Unusual Observations for EnergyRt

Obs  EnergyRt      Fit   SE Fit  Residual  St Resid
 29   94.1176  93.3574  14.1851    0.7602      0.06 X

X denotes an observation whose X value gives it large leverage.


Means for Covariates

Covariate   Mean  StDev
CDPerctg   90.16  22.15


Least Squares Means for EnergyRt

Mockup    Mean  SE Mean     Tukey Comparison Notation
1        34.45    5.574            b
2        60.73    4.131            a
```

Appendix H
Qualitative Analysis Details

1) Criteria for Representative Scores of Performance Outcomes

Schedule Growth:

```
Variable    N  N*  Mean  SE Mean  StDev  Minimum     Q1  Median    Q3  Maximum
C1         14   0  2.32     2.89  10.83   -12.50  -2.32    0.00  8.23    25.76
```

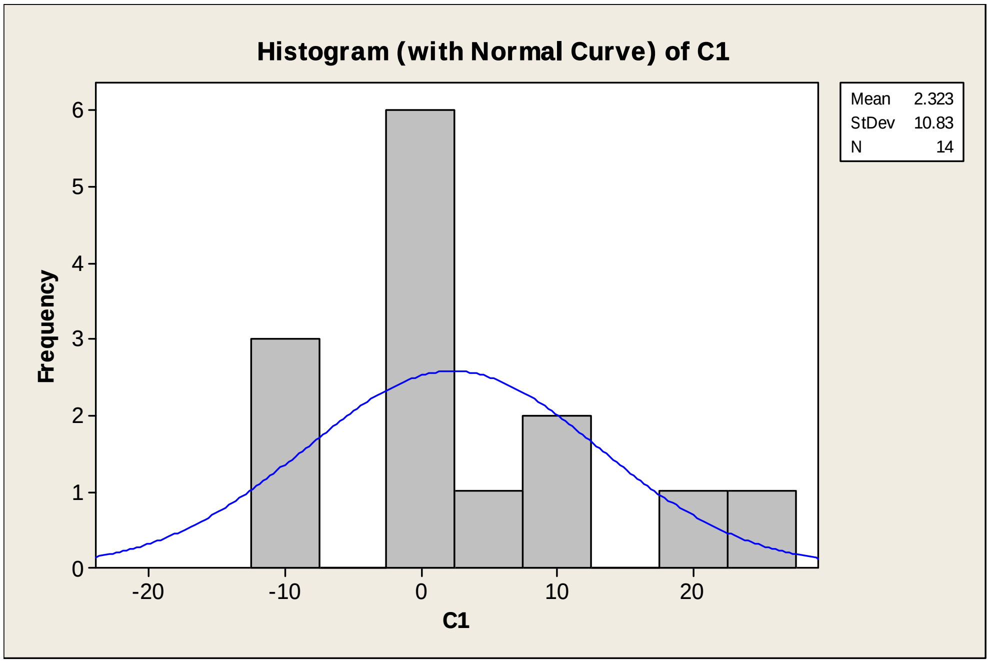


Figure F-16: Green Rate by Contractual Relations

Criteria: Less than 0: 1
Between 10 and 0: 0
Larger than 10: -1

Construction Speed:

```
Variable    N  N*   Mean  SE Mean  StDev  Minimum    Q1  Median     Q3  Maximum
C2         14   0  12563     2558   9572     1997  6442   10275  15735    36279
```

Criteria: Less than 5000: -1
Between 5000 and 15000: 0
Larger than 15000: 1

Delivery Speed:

```
Variable    N  N*  Mean  SE Mean  StDev  Minimum    Q1  Median    Q3  Maximum
C3         13   1  7397     1962   7073     1147  2965    5008  9425    22834
```

Criteria: Less than 4000: -1
Between 4000 and 12000 : 0
Larger than 12000: 1

Cost Growth:

```
Variable   N  N*  Mean  SE Mean  StDev  Minimum    Q1  Median    Q3  Maximum
C4        13   0  5.47     2.12   7.65    -4.72  0.00    3.62  9.83    22.02
```

Criteria: Less than 0:1
Until 5%: 0
Larger than 5%:-1

Unit Cost:

```
Variable   N  N*   Mean  SE Mean  StDev  Minimum    Q1  Median     Q3  Maximum
C5        14   0  130.1     14.6   54.7     64.5  93.4   109.5  177.2    249.0
```

Criteria: Less than $100: 1
Between 100 and 180: 0
Larger than 180: -1

Intensity:

```
Variable   N  N*   Mean  SE Mean  StDev  Minimum     Q1  Median     Q3  Maximum
C6        13   0  3.747    0.561  2.021    1.248  2.371   3.386  4.479    9.078
```

Criteria: Less than 2: -1
Between 2 and 6: 0
Larger than 6: 1

Turnover Q:

```
Variable   N  N*   Mean  SE Mean  StDev  Minimum     Q1  Median      Q3
C8        12   6  9.417    0.679  2.353    3.000  9.000  10.000  10.750

Variable  Maximum
C8         12.000
```

Criteria: Less than 8: -1
Between 8 and 11: 0
Larger than 11: 1

Syst Q:

```
Variable   N  N*    Mean  SE Mean  StDev  Minimum      Q1  Median      Q3
C9        12   0  12.167    0.683  2.368    7.000  10.500  13.000  14.000

Variable  Maximum
C9         15.000
```

Criteria: Less than 10: -1
Between 10 and 14: 0
More than 14: 1

Overall Q:

```
Variable   N  N*    Mean  SE Mean  StDev  Minimum      Q1  Median      Q3
C6        12   5  18.333    0.582  2.015   13.000  18.000  19.000  19.750

Variable  Maximum
C6         20.000
```

Criteria: Larger than 20: 1
Between 17 and 20: 0
Less than 17:-1

Energy rate:

```
Variable   N  N*   Mean  SE Mean  StDev  Minimum     Q1  Median     Q3  Maximum
C1        14   2  52.49     6.09  22.77    29.41  33.82   47.06  66.18    94.12
```

Criteria: Less than 40: -1
Between 40 and 62: 0
Larger than 62:

IEQ rate:

```
Variable   N  N*   Mean  SE Mean  StDev  Minimum     Q1  Median     Q3  Maximum
C2        14   2  64.15     5.05  18.90    33.33  53.33   63.33  81.67    93.33
1
```

Criteria: Less than 50:-1
Between 50 and 74: 0
Larger than 74:1

Green Rate:

```
Variable   N  N*   Mean  SE Mean  StDev  Minimum     Q1  Median     Q3  Maximum
C3        14   2  60.95     3.68  13.79    40.58  47.83   60.87  70.76    86.96
```

Criteria:
Less than 50:-1
Between 50 and 70: 0
Larger than 70:1

2) Results of the Pattern Matching Analyses

Table H-1: Pattern Matching Results for Owner Commitment by Project Performance

PI # 1 Owner Commitment	Categories	Project Codes	Cost	Time	Quality	Levels of HP	Project Score
More (+)	**1**	Project 1	0	-1	*	0	-1
Less (-)		Project 2	-1	-1	-1	0	-3
More (+)	**2**	Project 3	1	0	1	0	2
Less		Project 4	0	0	1	-1	0
More (+)	**6**	Project 11	0	0	1	1	2
Less (-)		Project 12	-1	0	0	0	-1
More (+)	**7**	Project 13	*	1	1	1	3
Less (-)		Project 14	0	1	0	-1	0
				Total Score (+)			6
				Total Score (-)			-4

Table H-2: Pattern Matching Results for Project Delivery by Project Performance

PI# 2 Project Delivery	Categories	Project Codes	Cost	Time	Quality	Levels of HP	Project Score
DB	**2**	Project 3	1	0	1	1	3
DBB		Project 4	0	0	1	1	2
CM	**3**	Project 5	*	*	*	0	0
DBB		Project 6	0	0	0	-1	-1
				Total Score (+)			3
				Total Score (-)			1

Table H-3: Pattern Matching Results for Contract Conditions by Project Performance

PI # 4 Contract Conditions	Categories	Project Codes	Cost	Time	Quality	Levels of HP	Project Score
More (+)	**2**	Project 3	1	0	1	0	2
Less (-)		Project 4	0	0	1	-1	0
More (+)	**4**	Project 7	*	1	1	1	3
Less (-)		Project 8	0	1	0	-1	0
More (+)	**5**	Project 9	0	1	1	0	2
Less (-)		Project 10	-1	0	0	0	-1
More (+)	**6**	Project 11	0	0	1	1	2
Less (-)		Project 12	-1	0	0	0	-1
				Total Score (+)			9
				Total Score (-)			-2

Table H-4: Pattern Matching Results for Integrated Design by Project Performance

PI # 5 Integrated Design	**Categories**	**Project Codes**	**Cost**	**Time**	**Quality**	**Levels of HP**	**Project Score**
More (+)	**2**	Project 3	1	0	1	0	2
Less (-)		Project 4	0	0	1	-1	0
More (+)	**3**	Project 5	*	*	*	0	0
Less (-)		Project 6	0	0	0	-1	-1
More (+)	**5**	Project 9	0	1	1	0	2
Less (-)		Project 10	-1	0	0	0	-1
More (+)	**7**	Project 13	*	1	1	1	3
Less (-)		Project 14	0	1	0	-1	0
				Total Score (+)			7
				Total Score (-)			-2

VITA

Sinem Korkmaz graduated from the Dokuz Eylul University, Izmir, Turkey in 2002 with a Bachelor of Architecture, Dokuz Eylul University, Izmir, TURKEY. She was born and raised in Turkey. Upon receiving her bachelors degree, she attended the architecture graduate school at Istanbul Technical University, Istanbul, Turkey and received a master of science degree under project construction and management option in 2004. Her master's thesis was titled: "Competitive Positioning and Sustainability of Turkish Construction Companies in the International Market."

During her PhD education at Penn State, she worked as an integrated research and teaching assistant for the Department of Architectural Engineering. During her education she organized the logistics of the summer program, helped with the construction coordination, and lead construction teams in Lame Deer, Montana between 2005-2007 for the American Indian housing Initiative (AIHI) program; developed the "Sustainability at Home" workshop series under supervision of Dr. David Riley with the 2006-2007 AIHI class; helped to coordinate Partnership for achieving Construction Excellence (PACE) Research Seminar at Penn State in Spring 2006; worked as the design documents coordinator between 2004-2005 in the design-build team of the sustainable Early Childhood Learning Center which is a 4000 SF facility built in Lame Deer, MT; developed 2D building drawing sets and site surveys, 3D CAD, Autodesk Revit, and daylighting models for the ECLC project . She also was a member of the Lean and green Research Initiative at Penn State.

Sinem Korkmaz also assisted the "AE 497H Design-Build: Tribal Housing" course that consists around 35 graduate and undergraduate students each semester with varied backgrounds including architecture and engineering for the Fall and Spring semesters of 2006-2007, and gave a lecture focusing on the high-performance green building delivery to the graduate and undergraduate students of the architectural engineering department in March, 2007 at Penn State.