Piloting Evaluation Metrics for Sustainable High-Performance Building Project Delivery

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Abstract: Sustainable high-performance buildings are being more widely adopted around the world to reduce energy costs and improve the well being of occupants. To achieve the set goals for these building projects within realistic financial and time constraints, superior planning, design, and construction processes are needed. The available literature lacks the descriptive project delivery metrics identifying scientific methods for providing insight or feedback about the performance of project delivery processes for sustainable high-performance buildings. This paper describes an exploratory study examining more than 100 variables in green project delivery to scientifically identify important metrics. Limited by a rather small sample due to the relatively young market of green buildings, the outcome of this paper, nevertheless, provides important direction for the continued development of meaningful metrics to assist in the establishment of a decision making support tool for project teams to facilitate optimum project delivery processes for sustainable high-performance buildings.

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Introduction

The adoption of green buildings is increasing globally due to the need for reducing resource consumption and contamination during a building's life cycle. Analysts expect $10 billion–$20 billion green building construction starts by 2010 [The McGraw-Hill Companies, Inc. (MCH) 2007]. A subset of green, sustainable, and high-performance buildings are designed and constructed to maximize the energy efficiency of the envelope, mechanical, and lighting systems to provide superior quality in the indoor environment for enhancing occupant well being (DOE 2006). These buildings are being widely adopted for their potential to reduce energy costs and improve the health and productivity of occupants. To achieve the set goals for sustainable high-performance building projects within realistic financial and time constraints, superior planning, design, and construction processes are needed. Therefore, it is important to understand the effects of project delivery attributes on their project outcomes.

There are substantial challenges to rigorous research in this field. This study is a pioneer effort for several reasons. (1) The literature review points to an extensive number of variables in the project delivery process of a green building. Building projects also differ in size, function, location, and systems; therefore, the number of variables in this area is increased. (2) Existing literature is mostly case based, limited in terms of the variables examined and depth of the data collection and analysis procedures. (3) The sustainable high-performance building project population is limited. The U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) is the most recognized green building assessment system in the United States. Although the number of registered projects under this system exponentially grew (i.e., 19,524 registered and 2,476 certified projects under LEED as of April 2009 [U.S. Green Building Council (USGBC) 2009]), the number of similar certified projects is still limited due to the variety of certification types (e.g., new construction, commercial interiors, existing buildings). Of these, an even smaller portion is truly sustainable high-performance projects: Kats et al. (2003) referred to an improved life cycle savings for gold and platinum LEED certified buildings that focus on energy efficient systems and improved indoor environmental quality (IEQ). (4) Project teams lack a system for recording their lessons learned in green building project delivery. Several Web-based green building databases [U.S. Green Building Council (USGBC) 2009; DOE 2006] allow public access but fail to explain project delivery characteristics of the case studies. In addition, high turnover rate in construction companies leads to difficulty in gathering essential information in this area. (5) The learning curve for the evolution of green building practices is still in its early phases. The knowledge base in this area is immature and the green building practices are yet to evolve.

Acknowledging these limitations, this exploratory research builds the first step in this area by piloting sustainable high-performance building project delivery evaluation metrics. To define these metrics, this paper utilizes quantitative techniques. The goal of the study is to contribute to the understanding of project delivery attributes for green buildings.

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Background

The major barrier for growth in the green building market is the perception of higher first costs associated with these buildings due to added personnel hours and use of innovative materials and technologies. The process used to deliver green building projects can be a remedy to this problem. Literature shows the owners' choice of project delivery systems (e.g., design-bid-build, design/build) can affect project outcomes including cost, schedule, and safety (Konchar and Sanvido 1998; Thomas et al. 2002; Ling et al. 2004). Different from traditional buildings, sustainable high-performance building delivery requires additional considerations (Riley et al. 2004). Recent research has shown that early introduction of and owners' commitment to "green" enables achievement of green goals at lower costs (Lapinski et al. 2006; Beheiry et al. 2006). Integrated design [Riley et al. 2004; Whole Building Design Guide (WBDG) 2009], team experience [General Services Administration (GSA) 2004], and early involvement of key project participants (Riley and Horman 2005) are also needed in these projects. The lack of understanding of a project's characteristics is likely to lead to defective delivery processes and high costs (Smith 2003).

The current building sustainability literature offers consensus-based metrics (i.e., LEED, Green Globes) that evaluate the sustainable features in a building project relating to energy, IEQ, site use, etc. Actual building performance is another focus area in the sustainable building literature that examines energy consumption, utilities, operations and maintenance, and occupant health (Fowler et al. 2005; U.S. EPA 2006; Green Building Alliance, "Improving the business case for green building: Towards a national data repository for self-reported metrics." Green Building Alliance Report, private communication, 2006). Other concepts such as whole building design [Whole Building Design Guide (WBDG) 2009] and integrated project delivery [The American Institute of Architects (AIA) 2009] offer innovative approaches to project delivery. However, they do not directly address green buildings nor attempt to examine the potential effects of project delivery attributes on project performance outcomes. As a result, the existing criteria on green buildings fail to address descriptive project delivery attributes that are scientifically identified to enable better project outcomes. To facilitate efforts to establish such criteria, green building project delivery evaluation metrics should first be defined.

Methodology

Motivated to fill the defined gap in the literature, this research focuses primarily on *green office building projects*. Fig. 1 below presents a process map of the methods followed for this study.

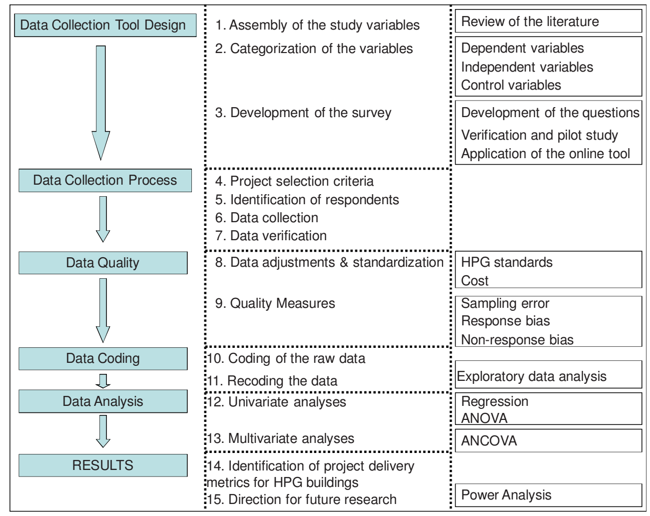

Fig. 1. Process map for the study methodology

Data Collection Tool Design

Selection and Categorization of the Study Variables

The design for the survey instrument started with the assembly and categorization of the preliminary set of metrics based on a detailed review of literature and industry sources. This review included (1) research of the relationship between the project delivery characteristics (e.g., delivery systems, procurement methods, contracts used) and performance outcomes for traditional buildings (Bennett et al. 1996; Molenaar and Songer 1998; Konchar and Sanvido 1998; Molenaar et al. 1999; Molenaar and Gransberg 2001; Chan et al. 2002; Thomas et al. 2002; Ling et al. 2004; El Wardani et al. 2006); (2) research on green building project delivery that pointed to areas such as early introduction of green concepts, owners' commitment to green, integrated design, cross-disciplinary work, team experience in similar projects, early involvement of key project participants, utilization of energy strategy, and simulation tools early in the design process [General Services Administration (GSA) 2004; Lapinski 2005; Riley and Horman 2005; Beheiry et al. 2006; Horman et al. 2006; Whole Building Design Guide (WBDG) 2009]; and (3) industry resources that provide lessons learned on green building case studies [DOE 2006; U.S. Green Building Council (USGBC) 2009; Green Globes 2009; Whole Building Design Guide (WBDG) 2009].

The literature review helped to identify two main types of variables in green building project delivery (Korkmaz et al. 2007) as attributes that can affect performance outcomes: independent and control variables. *Independent variables* can be controlled by project teams and constitute the main focus of this research. Seven independent variables identified in this study are owner's commitment to green, project delivery system, project team procurement, contract conditions, integration in design, project team characteristics, and construction process. *Control variables* include external environment components (i.e., the existence of qualified contractors, regulations) and project characteristics (i.e., project size, complexity, and building systems).

Additionally, the literature review aided this research in selecting project performance outcomes as the *dependent variables* that can be affected by the aforementioned attributes. Five project performance metrics were identified to measure outcomes of green building projects at construction completion: (1) schedule (i.e., delivery speed, construction speed, and schedule growth); (2) cost (i.e., cost growth, unit cost, and intensity); (3) quality from the owner's perspective [i.e., turnover quality, system quality, overall quality (Konchar and Sanvido 1998), and project cost performance—owner's satisfaction with the project cost performance might not align with the objective cost metric. As an example, an owner might be satisfied even though there is a high cost growth if the project had gone through a scope change initiated by him]; (4) construction safety measured by Occupational Safety and Health Administration (OSHA) ratings [i.e., record-

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Table 1. Preliminary Set of Evaluation Metrics for Sustainable High-Performance Building Project Delivery

Independent variables (process indicators)		Control variables
PI # 1—owner commitment	• Owner type	• Project type
	• Occupant type	• Building use
	• The party to propose "green"	• Building Size
	• The primary reasons to go for "green"	• Location
	• Timing of introducing "green"	• Project complexity
	• Importance of "green" for the project	• Pool of qualified contractors
PI # 2—project delivery system	• Project delivery system	• Regulations/legal constraints
	• Contractual terms used	• Onerous contract clauses
PI # 3—project team procurement	• Procurement method	• Building system characteristics
	Major team members	Foundation
	Mechanical subcontractor	Structure
	Electrical subcontractor	Exterior enclosure
	• Primary process for team selection	Architectural interior finishes
	• Importance of criteria in request for proposal (RFP)	Electrical
PI # 4—contract conditions	• "Green" requirements in the contract	Controls
	• Contractual relations for:	Site
	Core team members	• Building high-performance green (HPG) features
	Consultants	Elements to increase energy efficiency
	• Contract incentives/penalties	Heating system
PI # 5—design integration	• Timing of participants' involvement	Boilers
	Core team members	Ventilation and cooling
	Consultants	Chillers and piping
	• Involvement of a "green" consultant	Heat and power system
	• Level of integration	Entire façade continuity for vapor barrier
	• Use of quantitative metrics	Mechanical system design
	• Use of energy and lighting simulations	Dependent variables (performance metrics)
	• Use of envelope mock-ups	• Schedule performance
PI # 6—project team characteristics	• Team members' experience	Construction speed
	With similar facilities	Schedule growth
	With HPG buildings	Delivery speed
	With the delivery system	• Cost performance
	• Team's prior experience as a unit	Cost growth
	• Team communication	Unit cost
	• Team chemistry	Intensity (unit cost/total time)
	• Owner-team relation	• Quality performance (owner's satisfaction)
	• Owner's capability	Turnover quality
	• Owner's ability for team procurement	System quality
	• Owner's ability to define scope	Overall quality
	• Owner's ability to make decisions	Project cost performance
PI # 7—construction process	• Use of envelope mock-ups	• Levels of sustainable high performance
	• Subcontractors' education level on "green"	Energy performance
	• Level of completion for the CDs	IEQ performance
	• Quality of workmanship	Level of green/sustainability
	Envelope	• Safety (OSHA measures)
	Mechanical, electrical, and plumbing (MEP) systems	RIR
	• Quality control inspections	DART
	Envelope	Lost time case rate (LTC)
	MEP systems	Lost work days (LWD)

able incident rate (RIR), days away, restrictions, and transfers (DART) rate, lost time case rate, and lost work day rate]; and (5) level of achievement in sustainable high-performance standards. Although the literature suggests that higher level LEED certified buildings might be considered high performance (Kats et al. 2003); this research without bias prefers to adopt energy, IEQ, and green performance metrics instead of simply evaluating the projects' LEED certification levels. Each of these metrics uses the percentage of points achieved based on the LEED-new construction (LEED-NC) criteria. Based on the aforementioned definitions, over a hundred variables were identified as summarized in Table 1.

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Development of the Survey

After the preliminary set of metrics was established, survey questions were developed accordingly. Prior studies conducted on project delivery (Konchar and Sanvido 1998; El Wardani et al. 2006) guided this phase. Once the survey was developed, it was first verified by receiving industry professionals' feedback at the Partnership for Achieving Construction Excellence (PACE) Roundtable at Penn State in 2005. Subsequently, a pilot study using this survey instrument in face to face interviews was conducted on seven recently completed green office building projects in the Washington, D.C. area to (1) collect data on project delivery attributes and project performance outcomes; (2) test the developed survey; (3) eliminate as many variables as possible that do not pertain to green building project delivery; and (4) enable a more detailed study focused on the metrics that may affect green building project outcomes. The pilot study resulted in a final survey that included 42 project delivery processes and project performance related questions that are a mixture of the Likert scale, categorical, numerical, and open-ended types. The survey and the types of variables for each question can be seen in Korkmaz (2007). A commercial Web-based survey package was used for the survey application. This tool made automatic coding of the collected data and instant review of the submitted data by researchers possible. It also enabled the respondents to complete the survey at several sessions if they logged on from the same computer.

Data Collection Process

Project Selection Criteria

Researchers developed a set of criteria to minimize the variability in data sets. The study focused on *office buildings* in the United States from both public and private sectors since they constitute a large pool of green buildings due to their potential long-term benefits to business owners (e.g., improved productivity of employees). Focus on *new construction* was also prioritized in the project selection since sustainable and high-performance strategies followed in renovations or tenant fit outs can differ. In the project selection process: (1) industry publications that include green building case studies; (2) personal communications with industry members; and (3) Web-based U.S. Green Building Council (USGBC) (2009) and DOE (2006) green building databases were used. The primary list of green office/new construction projects developed for this research included 209 projects, which are mostly certified under LEED-NC.

Identification of Respondents

Project managers that have worked on the selected projects for any of the major parties (e.g., owners, designers, or contractors) were also identified using the same sources for finding the projects. Identified project managers were then invited to participate in this research through telephone calls and/or e-mails. Once the project managers responded with interest, the researchers e-mailed the on-line survey link to them and also asked for contact information of other major project participants. Several spreadsheets were used to store target project and respondent information and were updated as contact status changed.

Data Collection and Verification

Sixty-one of the 209 project managers contacted contributed to the on-line survey representing a 30% response rate for the initial data collection. However, the data showed that 21 of these projects did not comply with the research criteria due to their focus on interior finishes. The response rate was increased by a follow-up study where additional respondents were contacted to complete the unanswered questions within the returned surveys.

Data verification is essential when using various data collection methods (i.e., Web-based surveys, telephone calls, e-mails, and face-to-face interviews). A method used to increase the response rate also helped researchers in the data verification process: contacting various project participants (e.g., owners, project managers, estimators, and architects) from the same project team as respondents for various sections of a single survey. This procedure helped verify the responses through cross-referencing overlapping questions. When discrepancies among respondents occurred, the researchers followed up with them to resolve the conflicts. Other sources of green building data such as Web-based case study databases and green building publications were also used to verify the collected survey data. Researchers also checked the collected data (e.g., unit cost, delivery time) during the statistical analysis stage to detect any outlier data points that may have resulted from misinterpretations or errors of the data collection process. For example, delivery time for one of the projects showed as an outlier in the analysis stage. When the researchers called the respondents to verify that data point, they realized that the construction had stopped for over a year due to owner related reasons. The extreme value for the project's delivery time resulted from the respondent providing only the start and end dates of construction. Such data was corrected accordingly.

Data Quality

The survey used several techniques to assure the quality of the data collected. First, LEED criteria were adapted to measure project levels of sustainable high performance. LEED scorecards were collected for LEED certified projects. For non-LEED projects, specific questions were added to the survey (Korkmaz 2007). A rate of achieved points out of the possible LEED points was used to avoid data coding error due to the slight changes in LEED-NC versions used by the study projects. Second, RS means construction cost database 2006 was used to adjust building costs for different locations and years. Third, location, organization, project team, and project delivery system variety in the study sample were prioritized to overcome sampling error. Lastly, data collection techniques and coding accounted for possible response and nonresponse biases. As an example, all project participants for each project (i.e., owner, contractor, designer, key consultants, and subcontractors) were included in the data collection process for the "team characteristics" evaluation to avoid response bias that could result from using only one team member's subjective opinion. The responses were coded based on the whole teams' average scores. Similarly, the researchers followed up with participants to ensure inclusion of the projects at the lower end of the sustainable high-performance scale to avoid nonresponse bias. This bias could result from the project participants' unwillingness to provide data on low performing projects, skewing the sample toward the best performing ones.

Data Coding

After respondents completed the Web-based survey, responses stored at the online repository were extracted to a spreadsheet as coded data. Nonresponse data were also transferred to this spreadsheet, as the respondents were followed-up. The questions were categorized in the spreadsheets based on the research propositions

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for the ease of data analysis. The coding was changed as the categories were combined based on the exploratory data analysis (EDA) to reduce the number of predictors within the variables. For example, one of the independent variables, a procurement method used for the major team members, had six predictors (i.e., sole source selection, qualifications-based selection, best value source selection, fixed budget/best design, low bid, and competition). Among these predictors, sole source and qualifications based selection were the most selected choices for the procurement method for the designer. A minimal number of selections occurred for the rest of the predictors in the data set. Therefore, EDA reduced the number of predictors to the following three for this specific variable: sole source selection, qualifications based selection, and the other. In the next step, variables were categorized under continuous and categorical scales to guide selection of the statistical analysis methods to be used (e.g., regression can be used for detecting associations between continuous dependent and independent variables). After the coding, the data were exported to a statistical software package: Minitab.

Data Analysis

Upon completion of the data collection, researchers analyzed the data using a quantitative analysis approach. Overall, the statistical analyses employed for this research examined the association between project delivery process attributes and project performance outcomes at construction completion.

The study first used univariate analyses to see if a relationship existed between each independent and dependent variable. One-way ANOVA was used to ascertain whether means-dependent variable values differed according to the levels of categorical independent variables. Regression analysis was also used to detect association between dependent and continuous independent variables at this stage. Residuals were checked for normality and equal variance assumptions. One-way ANOVA and regression analyses were repeated for the transformed variables. Significant relationships (p-value<0.05) and relationships with the potential to become significant with larger sample sizes (p-value<0.2) were recorded. Following this procedure, the Bonferroni correction, a method of calculating a stricter significance level for hypothesis testing when multiple tests of statistical significance are run using the same data, was used since at the 0.05 significance level 5% of the hypothesis tests might appear to be significant by chance.

In the next step, the study employed multivariate analysis, where the significant independent variables selected (p-value <0.05) in the univariate analysis stage and the control variables were included in the analyses for each dependent variable. The literature recommends the use of analysis of covariance (ANCOVA) when the study involves mixed types of data (i.e., continuous and categorical) for independent variables, and continuous data for dependent ones (Garcia-Berthou 2001). ANCOVA combines regression methodology with ANOVA to evaluate the effect of the covariates (continuous variables) on the dependent variable and enables the comparison of treatments (Kuehl 2000). Therefore, ANCOVA was used to test whether the addition of the covariate (continuous variable) is significant in reducing the experimental error and if the treatment differences are significant based on the adjusted treatment means [treatment means are adjusted to the value of the significant covariate (Kuehl 2000)]. Normality assumption tests and transformation to satisfy the normality assumptions were also performed. Tukey pair wise comparisons were used to detect the means that are significantly different from each other. The significant covariates and categorical variables (p-value<0.05) were recorded. The extensive number of variables to be investigated, numerous levels associated with some of the independent and control variables, and the limited sample size of the study hindered the abilities of the quantitative analyzes at this stage.

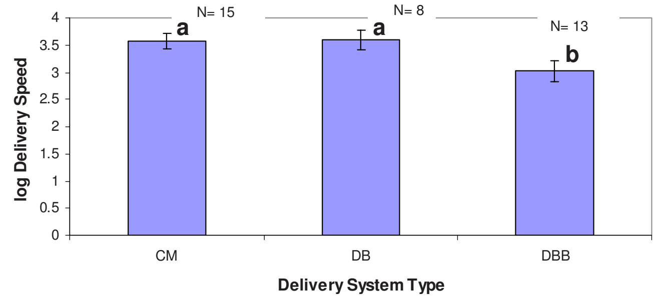

Fig. 2. Delivery speed by the delivery system type

Results

The final data set included 40 green office-building projects. While the majority of the study projects are commercial offices, the data set also included projects that are close to office buildings in function or have minor additions (e.g., retail banks, government/civic structures, courthouses, and office buildings with laboratory additions). Nearly one-half of the study projects are less than 50,000 square feet (SF) in size and about one-fifth are in the range of 50,000–150,000 SF. Among these projects, 42% are publicly owned, 45% privately owned, with the rest constructed by developers. Primary owners occupy 85% of these buildings. Of the study projects, 40% were delivered using the construction management at risk (CMR) delivery method, 25% design/build (DB), and 35% design-bid-build (DBB). Safety metric was not included in the study analysis due to a lack of data points collected on its variables.

Summary of the Univariate Results

The univariate analysis enabled this study to determine the limited set of variables to be used in the multivariate analyses and observe patterns to select the evaluation metrics for sustainable high-performance building project delivery. This analysis examines the relationship of each identified independent variable for one dependent variable at a time. The means of the categorical independent variables in the data set were tested using one-way ANOVA, while the continuous variables were examined using regression analysis. For each test, the variables that only satisfy 95% confidence level ($p<0.05$) were reported. Tukey comparisons, a pairwise comparison to compare each treatment mean with each of the other treatment means, were also conducted under the one-way ANOVA procedure (Kuehl 2000). Korkmaz (2007) gave the descriptive statistics for the significant variables and the Tukey comparison outcomes in greater detail. Fig. 2 presents an example for the results of the mean tests using a (9.26, SE 1.74) notation, where the first value describes the mean and the second value reports the standard error of the mean. Additionally, an (ab, a, b) designation is used to illustrate the Tukey comparison results in this study, where a and b represents significant difference between means and ab stands for insignificant differ-

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Table 2. Screening Table Example Based on the Univariate Significance Levels for Independent and Dependent Variables

Independent variables (process indicators)		Dependent variables (performance metrics): Schedule metrics			Cost metrics			Quality metrics			Sustainable high-performance metrics		
		ConstSpd	DelSpd	SchGrw	UnitCost	Intensity	CostGrw	TurnQ	OveralQ	SystQ	EnergyRt	IEQRt	GreenRt
Construction process	CDPerctg									O	■	O	■
	SubsEd							■				O	
	QworkEnvlp									■	■		O
	QWorkMech							■			■		O
	QControlEnv	O	O										
	QCont.Mech	■	■		O	■			■			O	
	Mockup	■	■			O	O		O		●		■
Project team characteristics	ExpFacO						O		■				
	ExpFacDB	O	O		O	■			O				
	ExpFacSub	●	■		■	●						■	
	ExpHPGO				■	■							
	ExpHPGDB				■	O							

Note: 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 ($p<0.001$); Exp=experience; Fac=similar facility; O=owner; DB=design builder; Sub=subcontractors; HPG=high-performance green features; and other abbreviations in this table can be followed with Table 1.

ence from the other treatment means. The number of observations for each level (N) and the variations observed are also presented in the results graph.

The graph indicates that CMR and DB outperform DBB in delivery speed: Mean log delivery speed for the DB project delivery system (4.05, SE 0.09) and for CMR (3.58, SE 0.18) are greater ($p<0.05$) than mean log delivery speed for the DBB type of project delivery system (3.03, SE 0.19). Such findings are useful for gaining insights about green building project delivery in the United States, yet restricted for making generalizations due to low sample size for each level. Until more robust analyses can be done, the outcomes of the study data can only be used to increase the understanding of evaluation metrics in this area. The results of the univariate analyses were reported by Korkmaz (2007) as shown in an example below (Table 2).

Univariate analysis summary tables show the following patterns in the data sets: (1) the significant independent variables are spread in the tables showing that the identified project delivery process indicators in this research are meaningful to investigate sustainable, high-performance project performance outcomes; (2) some of the significant independent variables in the summary tables are grouped under specific dependent variables and interpreting these patterns can assist project teams in their efforts to focus on the process indicators associated with their project specific goals; (3) some of the independent variables have a good run over the table (e.g., building a mock-up of the envelope system as seen in Table 2) illustrating the potential impact of certain independent variables on all of the dependent variables; and (4) the number of significant independent variables for each dependent variable shows that some of the dependent variables are more likely to be affected by project delivery process attributes, which include cost growth, construction speed, delivery speed, unit cost, energy rate, and green rate.

Summary of the Multivariate Results

At the multivariate analysis stage, the independent variables selected through univariate analysis and the control variables were analyzed for each selected dependent variable (i.e., cost growth, construction speed, delivery speed, unit cost, energy rate, and green rate). The method of calculation for measuring the dependent variables considered at this stage can be seen in Table 3 with the full list presented in Korkmaz (2007).

The significant outcomes of ANCOVA procedure are reported below and tabulated in Table 4 along with mean, standard error (SE), and number of observations (N) values for each level under the significant variables and percentage of variation explained by each model (R^2):

1. *Cost growth:* none of the covariates were found to be significant for cost growth. *Owner type* and *timing of the contractor's involvement in the project delivery process* have significantly different means. Mean cost growth for public

Table 3. Methods of Calculation for Measuring the Dependent Variables Considered at the Multivariate Analysis Stage

Dependent variables	Unit	Method of calculation
Cost growth	%	[(Final project cost-contract project cost)/contract project cost]$\times$100
Construction speed	SF/month	(Area/actual construction time in days)/30
Delivery speed	SF/month	Area/(total actual delivery time in days/30)
Energy rate	%	(Achieved energy points in LEED-NC/total possible points in energy section)$\times$100
Unit cost	\$/SF	(Final project cost/area)/building cost index
Green rate	%	(Achieved total points in LEED-NC/total possible points in LEED-NC)$\times$100

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Table 4. Summary of Multivariate Analyses Results

Dependent variables	Independent variables										Control variables	R^2 (%)
Cost growth	Owner type	p-value	Mean	SE	N	Timing of contractor's involvement	p-value	Mean	SE	N	—	67.08
	Public >		10.01	2.67	15	Design development >		15.48	3.53	4		
	Private	0.03[a]	2.18	2.45	14	Predesign	0.03[a]	1.23	3.29	3		
	Developer	0.39	6.13	3.59	4	Conceptual design	0.02[a]	5.08	4.26	3		
						Schematic design	0.32	1.31	3.06	4		
						Construction documents	0.68	7.44	2.27	2		
						Bidding	0.05[a]	5.62	2.27	10		
Construction speed	Owner type	p-value	Mean	SE	N	Timing of commissioning agent's involvement	p-value	Mean	SE	N	Size	82.54
	Developer >		4.09	0.16	4	Conceptual design <		3.11	0.14	5	Positive relation	
	Private	0.02[a]	3.52	0.08	17	Predesign	0.01[a]	3.95	0.14	5		
	Public	0.09	3.69	0.07	16	Schematic design	0.02[a]	3.70	0.10	8		
						Design development	0.01[a]	4.00	0.12	8		
						Construction documents	0.01[a]	3.89	0.14	4		
						Bidding	0.01[a]	3.92	0.15	4		
Delivery speed	Owner type	p-value	Mean	SE	N	Timing of contractor's involvement	p-value	Mean	SE	N	Size	93.66
	Private <		3.08	0.11	17	Conceptual design >		4.13	0.21	3	Positive relation	
	Public	0.01[a]	3.53	0.11	15	Predesign	0.39	3.61	0.19	10		
	Developer	0.20	3.95	0.26	4	Schematic design	0.01[a]	3.00	0.16	5		
						Design development	0.2	3.42	0.22	3		
						Construction documents	0.98	3.86	0.27	3		
						Bidding	0.01[a]	3.01	0.17	9		
Energy rate	Building envelope mock-ups before construction										Completion rate of CDs	43.26
		p-value	Mean	SE	N							
	Did not include >		60.73	4.13	22							
	Included	0.01[a]	34.45	5.57	11						Negative relation	

Note: >=higher; <=lower; SE=standard error; N: number of observations; R^2=percentage of variation explained by each model; and CDs =construction documents.

[a]Statistical significance ($p<0.05$).

owners (10.01, SE 2.67) is higher than those for both, private owners and developers, while it is only significantly ($p<0.05$) different from cost growth for private owners (2.18, SE 2.45). Mean cost growth for contractor's involvement in project delivery process at the design development stage is higher than those at all other stages.

2. *Construction speed: size* is a significant covariate with a positive relationship with construction speed. Owner type and *timing of the 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 higher than both private and public owners while it is only significantly higher ($p<0.05$) than private owners (3.52, SE 0.08). Mean log construction speed for commissioning agent's involvement in the project delivery process at the conceptual design stage is lowest ($p<0.05$) compared to those at all other stages.
3. *Delivery speed:* project size is the only covariate found to be significant for delivery speed and showed a positive association. Mean log delivery speed for *private owners* (3.08, SE 0.11) is lower than those for developers and for public owners (3.53, SE 0.11), ($p<0.05$). Mean log delivery speed for *timing of contractor's involvement* in the project delivery process at conceptual design is higher than those at all other 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 construction* resulted in significantly different means: mean energy rate for projects that did not include envelope mock-ups (60.73, SE 4.13) is higher ($p<0.05$) than that for projects that included envelope mock-ups (34.45, SE 5.57). This relationship contradicts the theoretical background, therefore, requires in-depth investigation with additional variables.

Limitations

The green building market is still relatively young and the total population of green building projects is rather small. The limited number of sustainable high-performance buildings in the market and missing values in the data sets limit the findings of this re-

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search. Several power analyses were conducted based on the study outcomes to understand the magnitude of a sample size needed for rigorous results in this research effort. As an example, the sample size 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. To detect a 10% difference between mean energy rates for the same independent variable, the sample size is 510 with a 0.8 power (Korkmaz 2007). 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.

Conclusions and Discussions

This study examined the associations between project delivery attributes and project performance outcomes of green buildings using quantitative methods. The analyzes contributed to the understanding of sustainable high-performance building project delivery evaluation metrics. More specifically:

1. 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 sustainable high-performance building project delivery. The observed relationships within this research can be validated as the data emerges.
2. The results of this study support the expected research outcomes:
   a. Timing of the contractors' involvement in projects and using envelope mock-ups before construction are strong process indicators affecting most of the performance outcomes as expected. It is important, however, to mention that using envelope mock-ups in the delivery process unexpectedly showed negative associations with energy and green rate under the sustainable high-performance metric. The use of envelope mock-ups in a project is an indicator that is believed to show high level of integration in the design process as it feeds the process with constructability reviews. Also it is believed to improve the construction process since field teams would be informed up-front through the use of a visual sample especially with complex and innovative envelope systems. The negative association between the "use of envelope mock-ups" metric and energy/green rates might be due to their use mostly for complex and mostly transparent systems. Strong associations show the importance of this metric; however, additional variables should be considered to explain the negative association in future studies.
   b. 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 the owner's ability to make decisions. However, elimination of these variables from the set of evaluation metrics is discouraged since they can become significant when combined with other variables.
   c. Relation patterns exist between the following variables: owner type/timing of contractors involvement in the project and cost growth/delivery speed, owner type/timing of commissioning agents involvement in the project and construction speed, and use of envelope mock-ups and energy rate.
   d. Size and "completion rate of construction documents at the time of construction" are the important control variables to affect project performance outcomes.
3. The quantitative analysis approach assisted the development of insights into performance metrics. Cost growth, construction and delivery speed, and energy and green rates are reliable performance metrics that can help understand the success of sustainable project delivery process. Team characteristics and quality metrics are subjective metrics. Although unit cost and intensity metrics are adjusted for year and location, their value is limited since the cost index does not consider construction types, systems used within buildings, or complexity. Seeking alternative ways to these metrics for more objective evaluation is a worthwhile effort.

A comparison of the study findings with Konchar and Sanvido (1998) verifies the limitations to this research field, show some similarities in lessons learned about project delivery methods, and reveal the differences between traditional and green building delivery. (1) Although Konchar and Sanvido (1998) worked on a large sample of projects ($N=351$), only three of its multivariate models (i.e., unit cost, construction, and delivery speed out of nine metrics) were able to explain more than 80% of the variation. This confirms the limitation of this research field due to high variation with its project-based nature and the need for large sample sizes for statistically significant outcomes. (2) The univariate findings of the study align with the Konchar and Sanvido (1998) findings about the delivery speed: DB and CMR outperform DBB. In the multivariate models for construction and delivery speed, both studies found project size to be a significant variable. (3) While Konchar and Sanvido (1998) focused on the performance differences of DB, CMR, and DBB project delivery methods for traditional projects; this study examined project delivery attributes including project delivery methods for better performance outcomes in green buildings with a focus on new construction/offices. The results of this study showed project delivery attributes such as timing of project participants' involvement in the delivery process and owner type being more important for successful project outcomes in sustainable high-performance building projects compared to the project delivery method used.

As illustrated in the power and sample size analyses, larger sample sizes yield the desired levels of statistical power in this type of 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. As the population of the sustainable high-performance buildings continues to expand, the findings of this research can be verified and supplemented using the described methods in this paper. Such verification can significantly show the most important project delivery attributes that lead to improved sustainable high-performance building project outcomes. This effort in the future can help create a decision-making support tool for project teams to facilitate the optimum project delivery processes for their sustainable high-performance buildings. For example, an on-line database that continuously is fed by input data on green building project delivery applications can assist project teams to map out their optimized project delivery processes based on their project goals (e.g., level of LEED certification, budget, and schedule) and project specifics such as building type, location, size, and scope. A weighted list of importance for project delivery attributes can also help project teams to improve their delivery processes, which would in return lead to improved project outcomes for sustainable high-performance buildings.

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