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The Pennsylvania State University

The Graduate School

College of Engineering

A COMPARISON OF UNITED STATES PROJECT DELIVERY SYSTEMS

A Thesis in
Architectural Engineering
by
Mark D. Konchar

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

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We approve the thesis of Mark D. Konchar.

Date of Signature

Victor E Sanvido
11/21/97

Victor E. Sanvido
Professor of Architectural Engineering
Thesis Advisor
Chair of Committee

10/20/97

William Bahnfleth
Assistant Professor of Architectural Engineering

10/20/97

Sidney Cohn
Emeritus Professor of Urban Design

10/20/97

Hossam El-Bibany
Assistant Professor of Architectural Engineering

10/20/97

Mark Handcock
Associate Professor of Statistics

Richard Behr
11/21/97

Richard Behr
Professor of Architectural Engineering
Head of the Department of Architectural Engineering

ABSTRACT

A project delivery system defines the relationships, roles and responsibilities of project team members and the sequence of activities required to provide a facility. Several systems have evolved over the years. Construction management at risk, design-build and design-bid-build are three principal project delivery systems used in the United States today. This research presents an empirical comparison of the cost, schedule and quality attributes of these three project delivery systems, using project specific data from 351 US building projects.

The study included collecting, checking and validating industry data, significance testing of univariate comparisons and the statistical development of multivariate linear regression models. A non-response study verified statistically that sample data was appropriate for analysis and representative of the industry from which it was drawn. Significance testing and multivariate comparisons used nearly 100 explanatory and interacting variables to explain project cost, schedule and quality performance. Several variables critical to project performance were also identified. Relationships between these variables and key performance metrics were identified through analysis of multivariate linear regression models.

An understanding of these relationships can help an owner better select the project delivery system most suited for their specific facility goals. Specific comparisons between delivery systems, performance metrics and six facility classes are discussed. Results and the level of confidence that surrounds each finding are presented. Furthermore, this study provides quantitative data to support the selection of a specific delivery system and greatly increases the understanding of individual system performance.

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GLOSSARY OF TERMS

Construction management at risk: Construction Management at Risk is a delivery system where the owner contracts separately with a designer and a contractor. The owner contracts with a design company to provide a facility design. The owner selects a contractor to perform construction 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.

Cost: Cost is the amount of money paid by an owner for a facility, measured in US dollars. Costs were limited to the design and construction of the facility and did not include land acquisition, extensive site work, process equipment or owner costs.

Design-bid-build: Design-Bid-Build is the traditional project delivery system in the US construction industry where the owner contracts separately with a designer and a constructor. The owner normally contracts with a design company to provide "complete" design documents. The owner or owner agent then usually solicits fixed price bids from construction contractors to perform the work. One contractor is usually selected and enters into an agreement with the owner to construct the facility in accordance with the plans and specifications.

Design-build: Design-build is a project delivery system where the owner contracts with a single entity to perform both design and construction under a single design-build contract. Contractually, design-build offers the owner a single point of responsibility for design and construction services. Portions or all of the design and construction may be performed by a single design-build entity or may be subcontracted to other companies.

Facility delivery process: The facility delivery process includes the activities required to provide a facility. Five major activities are: plan, manage, design, construction and operation.

Facility team: The facility team includes all parties who perform the activities in the facility delivery process. These may include the owner, architect/ engineer, constructor, design-build entity and subcontractors.

General building sector: The general building sector consists of non-residential markets including light industrial, multi-story dwelling, simple office, complex office, heavy industrial, and high technology facilities.

Project delivery system: A project delivery system defines the relationships, roles, and responsibilities of project team members and the sequence of activities required to provide a facility.

Schedule: The schedule is the time taken by the facility team to design and construct the facility and is measured in months.

Quality: Quality is the degree to which the facility met the expected facility requirements. Quality was measured by comparing the actual performance versus the facility user's or owner's expectations of the referenced building.

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CHAPTER ONE

INTRODUCTION

Project delivery systems have evolved over the years. Today's delivery systems have evolved from the medieval master builder. In these times, rulers had many resources and their resulting designs were grand in scale. Owners hired the master builder to design, engineer and construct an entire facility (Branca, 1987). This system dominated the construction world until early in the 20th century. As empires fell, owners were faced with limited resources. Project designs became more modest and project schedule durations decreased. These projects required a new type of master builder who could accurately forecast costs for projects. Ultimately, more master builders gained experience and entered the market, creating a highly competitive industry.

While competition grew steadily, continuous changes in technology and the increasing sophistication in buildings required specialization of design and construction services. This led to the traditional design-bid-build delivery system. In design-bid-build, services are divided by specialty area and then competitively bid to consultants and contractors. They in turn subcontract portions of the work to other specialists. This offered clients a sequential design, bid, then build approach.

As the specialization of services increased, single source master builder approaches to delivering projects decreased. Design and construction entities were sharing information only at the end of design and during the construction process. Interaction, particularly during the design phase, was extremely low. This resulted in inefficient designs, increased errors and disputes, higher costs and ultimately longer schedules. Also, facilities were becoming more complex, demanding greater owner input and in-house cost, schedule and quality management (Potter, 1995). In the 70's and 80's this conventional approach became unacceptable to many clients and the construction manager was introduced. The construction manager's role was to provide input to the designer to increase the constructability of designs and to decrease schedule durations by overlapping design and construction phases.

In construction management at risk, the contractor usually has significant input in the design process and generally guarantees the maximum construction price. The range of services offered by construction managers, coupled with a direct advocacy between the owner and construction manager, created a team approach in project delivery (Borgstrom, 1995). However, substantial efforts by owners to downsize in-house project management manpower, costly disputes between design and construction parties and various levels of owner experience has forced several owners toward single source design-build contracting (Dell'Isola, 1987).

More recently the design-build delivery system has seen increased use. In design-build, projects are integrated by a single point of responsibility for design, construction, and project management (Branca, 1987). A design-build contract is an agreement between an owner and a single entity to provide a facility under a single contract. Portions or all of the design and construction may be performed by the entity or subcontracted to other companies. Design-build is now recognized for use in over half of the 50 US states and accounted for over 24 percent of the 286 billion dollars of non-residential construction put in place in 1996 (Design 96, Tarricone 96, US Dept. of Commerce 97). Congress recently enacted specific authorization that enables federal contracting officers to use the design-build project delivery system in the public sector (Design-Build Dateline, 1996). Similarly, civil and infrastructure industries have recently developed new applications of design-build to procure large highway and bridge projects (Powers, 1997). Consequently, with continued growth and its application to a variety of markets, there is a need to clearly distinguish the contractual and operational merits of design-build from its predecessors and other principal procurement methods.

Construction researchers have made substantial efforts to expand project delivery research in the past decade. Attempts to explore the success, failure and application of delivery systems have been documented through various case studies of high profile projects such as the Sydney Opera House and the Texas Motor Speedway (Reina, 1997, Capps, 1997). Opinion surveys of clients who frequently administer design and construction services have been successful in investigating attitudes toward specific delivery methods (Songer, 1996, Truong, 1996). Detailed analyses of builders and clients have explained variations in the way procurement systems are administered both privately and in the public sector (Fraga, 1996, Bruns, 1997, Myers, 1994). Other researchers have approached this research using empirical performance data.

Oberlender (1993) performed a quantitative study to identify factors known prior to the commencement of construction which are early warning signs of project cost and schedule growth. Pocock (1996) developed a method for measuring the impact of project integration on performance of public sector projects. The University of Reading Design and Build Forum (1996), using multivariate analysis techniques, compared the cost, schedule and quality performance of 332 design-build and design-bid-build projects recently built in the United Kingdom. These researchers have laid the groundwork for a more focused study of delivery systems in the US.

1.1 PROBLEM STATEMENT

Despite the research efforts discussed above, there is no study that can definitively show the quantifiable cost, schedule, and quality performance differences between construction management-at risk, design-build, and design-bid-build delivery systems in the US (Sanvido, 1996). Before theoretical research in this field can start, a performance-based, empirical investigation of the three principal delivery systems used in the US construction industry is needed. Furthermore, without an objective study of these modes of delivery, present day owners lack the basic knowledge that is critical in deciding which way they choose to deliver their facility.

1.2 OBJECTIVES

The purpose of this research study was to empirically compare the cost, schedule and quality performance of construction management at risk, design-build and design-bid-build delivery systems for US building projects. This research had three distinct objectives:

1. to develop, test and implement a method to collect detailed performance data from US construction projects,

2. to compare total project cost, schedule and quality performance between construction management at risk, design-build and design-bid-build delivery systems, and
3. to describe project characteristics which explain the highest proportion of variation in project performance measures.

1.2.1 SCOPE

The scope of the study was limited to measuring cost, schedule and quality performance of select categories of buildings. Cost and schedule dates for both design and construction were documented at the time of contract award and at project completion. Quality was limited to asking facility owners to measure the difficulty of the turnover process and the actual versus expected performance of each principal facility system. Tenant and process work items were not included. General building projects studied were completed within the past five years in the United States. Qualitative factors that described the project and team context were identified and measured. Specific definitions referenced terms and of cost, schedule and quality performance are described in the glossary of terms. Definitions of each project delivery system are discussed further in Chapter Two.

1.2.2 RELEVANCE

A study that objectively measures cost, schedule and quality performance of the major delivery systems in use in the US was needed for several reasons. For research to progress, performance differences between project delivery systems must first be identified, then described and their causes must be defined.

The industry would also benefit from an objective comparison in several ways. First, a private owner that has to decide whether or not to utilize a particular delivery approach, may have several concerns. One may be losing control over the delivery process. Another may be realizing cost, schedule and quality benefits. They usually base their decision on their experience or anecdotal evidence. A second case may be the general contractor who can deliver projects using any of the three systems and must convince an owner that one system better fulfills their facility needs. They have the same sources to base their decisions as the owner. Finally, public agencies governed by federal acquisition regulations have been frustrated by a history of poorly performing design-bid-build projects (Pocock, 1996). As these regulations change, government owners have project delivery choices and they need objective evidence to support selection of specific delivery systems based on their performance.

Never before has an empirical comparison been made of principal US delivery methods. The US construction industry will benefit from an unbiased investigation that outlines the specific relationships of cost, schedule and quality between principal delivery systems. An understanding of performance of these systems will help an owner better select the project delivery system most suited for their specific facility goal. Furthermore, the collection of quantitative data supporting the selection of the specific delivery system can greatly increase the understanding of these systems.

1.3 RESEARCH APPROACH

Since a limited amount of research has been performed on empirically evaluating project delivery methods, an investigation of the variables describing project performance was a critical first step. Concurrently, methods for economically and comprehensively collecting factual data on a large scale were analyzed. A data collection instrument had to allow the researcher to collect field data from a large cross section of the US construction industry. The selected data collection method had to also allow the researcher to thoroughly cross check data for accuracy. Research was divided into four distinct phases.

The first phase developed an instrument to collect and analyze project data in an objective manner. A comprehensive data collection instrument including quantitative cost, schedule and quality performance data was created and pilot tested with a taskforce of industry experts. Phase two used the data collection instrument to collect extensive project data from the US construction industry. Phase three used several data checking techniques to verify project data. These improved the consistency and accuracy of project data. A non-response study targeted a random sample of survey non-respondents to determine how well the sample represented the industry. Finally, the fourth phase tested several hypotheses to distinguish significant differences in delivery performance.

Multivariate linear regression identified those variables having the most impact on project delivery performance. Each of four phases of research is discussed below.

1.4 RESEARCH STEPS

1. Develop and test the data collection instrument and performance metrics.

This research benefited directly from the extensive interaction with an expert, industry taskforce organized by the principal research sponsor, the Construction Industry Institute (CII). Members of this taskforce provided continual input in all phases of the research particularly in topic definition, the brainstorming of survey questions, the development of principal definitions and metrics, and the review of results. They also identified several sources for project data.

This research required objective cost, schedule and quality comparisons. Input from the taskforce and methods from related literature shaped the development of seven metrics used for these comparisons. The design of performance metrics identified critical data for collection. Literature regarding project delivery systems, applied linear statistical modeling, survey research and construction contracts was examined and confirmed the existence of other explanatory data known to affect project performance. The researcher held numerous discussions with researchers conducting related studies within the US and abroad. Pertinent research from agencies such as the CII, the Design-Build Institute of America (DBIA), the Associated General Contractors of America (AGC) and other research institutions was also studied.

Evaluating the performance of project delivery systems required a large amount of project specific data collected directly from the US construction industry. The success of this data collection depended largely on the length and complexity of the data collection instrument [Dillman, 1978]. For this reason it was critical to pilot test the data collection instrument. The initial data collection instrument contained extensive questions and required much project data. The first five sections collected data used for calculating seven performance metrics. The latter sections were based on factors identified in the literature and by the taskforce, which were known to affect project performance. After review by the Penn State statistical consulting center, the data collection instrument was tested on 25 projects supplied by the taskforce. Based on the analysis of the respondents' interpretation of the questions and the value of the data in the responses, the instrument was modified and retested on an additional 25 projects. Testing in this fashion allowed the researcher to rewrite ambiguous questions and shorten the instrument by discarding unnecessary or unsuccessful questions.

The final version of the Project Delivery System data collection instrument is located in Appendix B. The final version examined the three principal types of project organization being studied, considered seven different contract types and provided data for seven critical performance metrics. The instrument also collected information on nineteen characteristics of the project team and its environment, nine classes of major building systems, the success criteria for the project and lessons learned from the project.

2. Collect data.

Data was collected by mail, fax and through phone interviews. Telephone interview techniques increased the response rates typically obtained in mail surveys and assisted respondents with questions regarding survey content. The data collection instrument was mailed to a random industry sample targeting companies in several professional organizations. These were the Construction Industry Institute (CII), the Design-Build Institute of America (DBIA), the Associated General Contractors of America (AGC), the Partnership for Achieving Construction Excellence (PACE), the US military and Penn State architectural engineering alumni. Members of these organizations were targeted because they represent a good cross section of contractors who design and build projects within the general building sector of the United States.

Projects were drawn from the general building sector of the industry. They were later classified into six facility classes based on detailed descriptions of their building systems (See section 5.3.2). They are light industrial, multi-story dwelling, simple office, complex office, heavy industrial and high technology. Where possible, respondents were asked to select pairs of projects that were similar in scope, yet different in delivery system. For instance, one which used construction management at risk and the other which used design-build or design-bid-build.

3. Verify data.

Every project response was scrutinized for errors in the project data. Follow up phone interviews were made to complete information and check project facts. In each case where the respondent was not the owner, facility owners or users were contacted directly to obtain quality data. Finally, data was sorted and independently entered three times into a Filemaker® database and Microsoft Excel® spreadsheets. Additional data checks by people trained by the researcher detected and corrected several recording errors and increased the consistency and accuracy of project data collection, organization and entry.

A non-response study was conducted to verify the appropriateness of collected data. By gaining additional project data from a sample of those who did not respond during the initial data collection effort, the researcher was able to validate the fact that collected data was representative of the industry from which it was drawn.

4. Analyze Data.

Using Minitab® statistical software, each project was first classified based upon its origin, type and source. For each of these classifications, data sets including size, cost, delivery system, owner type, facility type, and respondent origin were calculated. Next, descriptive statistics such as standard deviations, medians, means and ranges were calculated for each key metric. These statistics were repeated for the original sample, the non-response sample and the combined sample. Then, hypothesis testing and multivariate regression used the entire sample for each key metric. Finally, relationships between empirical results and qualitative survey data, such as team and building characteristics, were investigated.

1.5 RESEARCH RESULTS

This study produced several important results. These are:

1. The development of an effective method to obtain quantitative cost, schedule and quality data from the US construction industry,
2. The execution of a non-response study to verify the appropriateness of the collected sample to the industry from which it was drawn,
3. A direct comparison of construction management at risk, design-build and design-bid-build project delivery systems through the evaluation of 351 US projects, and
4. The identification and description of project characteristics that explain the highest proportion of variation in project performance measures.

1.6 READER'S GUIDE

Chapter One provided an overview of this study. Chapter Two presents a review of related project delivery system research, project delivery systems, construction contracts, applied linear statistical modeling and survey research methods. This chapter illustrates the current state of project delivery research. It distinguishes between the anecdotal and empirical research. Chapter Two summarizes the work of others and identifies where the researcher is departing from their work.

Chapter Three identifies the variables included in this research by defining a project delivery research framework. Performance metrics are described and defined. Several expected relationships are discussed as they relate to project delivery performance and data collection. Chapter Three ends with a description of the data collection instrument.

Chapter Four justifies the detailed data collection and analysis methods implemented in this research. It explains the metric and question development, data collection, data checking, and analysis. This chapter also explains how the findings of other researchers guided the methodology for this study.

Chapter Five explains initial data collection response rates and verification procedures performed before combining data samples. It also discusses data standardization procedures such as the cost indexing of projects and the classification of projects by facility type. Chapter Six describes the detailed results of project data analysis. It illustrates the significant findings based on standard testing procedures and summarizes regression results into primary and secondary findings. Chapter Seven summarizes results, acknowledges the limitations of this research, provides an outline for future research and discusses the contributions of this study.

CHAPTER TWO

LITERATURE REVIEW

This chapter describes the definitions of each principal project delivery system studied in this research. Related project delivery research is discussed with specific mention of several empirical research studies recently completed in the US and abroad. Chapter Two summarizes the work of other researchers and gives a background to the current state of project delivery system research in the construction industry.

2.1 PROJECT DELIVERY SYSTEMS

Project delivery systems are referred to in many different ways. In this thesis, a project delivery system defines the relationships, roles, and responsibilities of parties and the sequence of activities required to provide a facility. More commonly stated, delivery methods "describe the roles of participants, the relationships between them, both formal and informal, the timing of events and the practices and techniques of management that are used" (Ireland, 1982).

While many delivery systems are available, this thesis considers the three most common project delivery methods employed in the US today. These are construction management at risk, design-build, and design-bid-build. Two other commonly used systems are agency construction management and program management. As with construction management at risk, these systems offer an owner a consultant type relationship for planning and management, yet they differ slightly in that the program manager does not perform or hold construction contracts (Associated, 1991). Multiple-prime contracting is another project delivery system where the owner holds separate prime contracts for the design and construction of each separate building system (Lynch, 1996).

2.1.1 DEFINITIONS

While several variations do exist for construction management at risk, design-build and design-bid-build, the following definitions represent the basic understanding of these project delivery systems used in this thesis.

Design-Bid-Build is the traditional project delivery system in the US construction industry where the owner contracts separately with a designer and a constructor. The owner normally contracts with a design company to provide "complete" design documents. The owner or owner agent then usually solicits fixed price bids from construction 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. These three steps follow sequentially, characterizing design-bid-build as the separation of design and construction disciplines. Assuming there are no changes to the plans, this results in a firm cost for the project and a somewhat simpler selection process. However, the owner must perform two selections, first the architect, and second, the constructor. The constructor is selected after the completion of design, thus omitting constructability reviews [Associated, 1991]. This separation and the subsequent lack of a team approach from the beginning, typically makes the owner and contractor adversaries. They have different financial interests which can lead to disputes and costly changes.

Construction Management at Risk is a project delivery system where the owner contracts separately with a designer and a contractor. The owner contracts with a design company to provide a facility design. The owner selects a contractor to perform construction 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. This system represents a departure from the traditional design-bid-build method in two distinctive ways. First, the client has the opportunity to engage the construction entity much earlier in the design process. Early brainstorming sessions which involve the constructor offer the owner great advantage [Capps, 1997]. The second distinction is a result of the first. Planning, through this early integration of team players, allows for phased design, advanced ordering of long lead items and early construction start dates for critical excavation and foundation packages [Branca, 1987]. These operational distinctions are slight while comparing them to design-build delivery. However significant difference is noticed contractually.

Design-Build is a project delivery system where the owner contracts with a single entity to perform both design and construction under a single design-build contract. Contractually, design-build offers the owner a single point of responsibility for design and construction services. This is different from construction management at risk and design-bid-build, where the owner must administer at least two separate contracts. Portions or all of the design and construction may be performed by a single design-build entity or may be subcontracted to other companies. Even in cases where the design-build entity subcontracts directly or partners for design, the owner maintains the same, single contact. The difference between design-build and construction management at risk is sometimes slight (Tulacz, 1995). Private and public sectors alike have seen more requests for design-build, a consequence of a further evolution of customers who expect a broader range of service from a single entity.

2.1.2 COMPANY CONFIGURATIONS

Each of these delivery systems can be performed by teams that are configured in different manners. Various team configurations exhibit the wide variety of alternative project delivery systems which have been introduced. These teams are drawn from companies that have different capabilities. Several company configurations found are (Sanvido, et al., 1996, p. 5):

- "construction/ project managers and designers that act as agents of the owner;
- constructors, designers or project managers that act as brokers and subcontract all activities;
- designers or construction contractors that self perform select disciplines, typically architectural, structural and finish items and subcontract the balance;
- contractors with full service in-house design, fabrication and construction installation ability;
- contractors with full service in-house design and construction ability;
- contractors with in-house design and construction management ability; and
- design / construction joint ventures and strategic alliances."

In these organizations above, the word "designer" can also mean "specialty consultants," and the word "contractor" includes "specialty subcontractors." Also note that above classifications apply to construction management at risk, design-build or design-bid-build delivery systems.

2.2 RELATED STUDIES

Several areas have been explored to document the use of project delivery systems. Numerous case study attempts have explored instances of success and failure, the advantages and disadvantages of systems and unique applications of procurement systems (Reina, 1997, Capps, 1997). Opinion surveys of clients who frequently administer design and construction services have been successful in investigating the attitudes toward specific delivery methods (Molenaar, 1995, Songer, 1996, Truong, 1996). Several more 'in depth' case studies of industry builders and clients, such as the US Postal Service, explain variations in the way project delivery systems are administered both privately and in the public sector (Fraga, 1996, Bruns, 1997, Myers, 1994). Several researchers have collected specific project data from the industry through survey research (Bennett, Pothecary and Robinson, 1996, Pocock, 1996).

The Design-Build Institute of America (DBIA) has compiled many articles related to design-build practice and project specific case studies. These publications (Master..., 1996, Fraga, 1996) offer insights to the effectiveness of particular systems but do not offer a direct comparison of their merits. Songer (1996) has compiled a substantial reference list of design-build literature which includes several articles containing general and anecdotal information with limited empirical research findings.

The following paragraphs describe three main types of project delivery system research. These are: the general impacts of planning and management functions on project delivery, opinions on delivery system benefits and empirical studies of project delivery systems.

2.2.1 PLANNING / MANAGEMENT EFFECTS ON PROJECT DELIVERY

Project planning and management strategies have been explored in many ways. In particular, their potential to positively or negatively effect the outcome of a project has received a great deal of attention. One such study (Songer, 1992) examined and developed an improved approach to owner planning of the design-build contract management process for public sector agencies. This study created a process model specifically designed for the administration of public design-build contracts. It identified and incorporated planning, analysis and pivotal decisions made by the owner.

Another study focused on the relationships between the levels of pre-project planning and subsequent cost, schedule and contract modification outcomes (Bruns, 1997). The correlation used historic data from 37 projects completed within the University of Texas System. Using 11 previously developed pre-planning criteria, Bruns investigated the extent to which these criteria were correlated with project performance. Results indicated a positive correlation in a single case. This occurred between the managers' individualized responses to the defined pre-planning criteria and when they were asked to subjectively rate the overall pre-planning effort on a project. Cost, schedule and contract modifications indicated no direct relationships to pre-project planning. The calculations used to create the pre-planning index utilized an aggregate score for all 11 criteria. If these were taken individually they might have introduced different relationships. Other reasons for the potential lack of correlation were recognized. Time lapse between project completion and the pre-planning questionnaire might have affected a manager's perspective of the pre-planning effort actually implemented. Also, pre-planning efforts were not formally practiced on many of the projects.

Engineering Procure Construct (EPC) contracts used in the process industry are a form of single source design-build contracting. McFall investigated the impacts of information management on project success by using the engineer-procure-construct process model (1997). Using process activities within this model, a methodology was provided for predicting the impact of proposed information process changes on project cost and schedule performance. The research team, using the large level 164 activity EPC model, 'micro-modeled' only those activities known to be affected by a proposed process change. Three specific information management strategies were identified.

They are data management, document management and information sharing. By speculating how the manipulation of these strategies could alter the process outcome, the team could prepare separate models for comparison. This led to an analysis of average performance improvement calculated by comparing speculated, present and historical EPC process models. Results indicated that information management practices can significantly improve project performance. Furthermore, this research has identified a method which allows a project team to manipulate certain activities in the EPC process and consequently predict the effect those changes could have on project schedule and cost outcomes.

Although these studies did not directly measure project performance, they greatly improved the understanding of certain factors, which when acting as a group, might be associated with excellent or poor project performance. The following list summarizes the pre-planning and information management criteria identified in the above referenced works.

1. Scope definition,
2. Customer participation,
3. Project objectives and priorities,
4. Execution approach,
5. Pre-authorization design data,
6. A/E selection and qualifications,
7. Communications,
8. Project controls,
9. Alternatives analysis,
10. Constructability,
11. Risk assessment,
12. Data management,
13. Design and materials management,
14. Document management, and
15. Information sharing.

2.2.2 NON-EMPIRICAL PROJECT DELIVERY RESEARCH

Research efforts designed to collect perspectives, opinions or feelings about selected project delivery systems are presented. While these studies are limited in terms of empirical data, they offer reasons why clients select certain project delivery systems.

Truong quantified an owner's confidence level that the choice to use one delivery method over another would produce improved project results. This study compared design-bid-build and design-build. This research analyzed types of owner organizations and types of projects for which it was believed design-build was best suited. It then evaluated project characteristics by which design-build was consistently the method of choice (1996).

Truong collected rankings of project objective criteria from 51 respondents. These included items such as the potential to reduce project time and cost, the potential to involve the constructor early in the design process, the flexibility to accommodate design changes, various levels of owner experience, reduced litigation and other criteria surrounding design and planning decisions. A weighted decision factor was calculated by combining rankings with information collected during a literature survey on the effective use of design-build. Based on this factor and the number of projects in each category, an assertion was made as to the desirability of using design-build. Possible outcomes included: desirable, potential or no valid conclusions. A variety of conclusions were reached amongst the different owner organizations and project types. This research also identified objectives that a variety of owners were consistently basing project delivery selection decisions.

A more extensive survey by Molenaar (1995), tested the existence of primary factors for selecting design-build. This study was restricted to public sector owner organizations such as local, state and federal agencies. Using a combination of expert owner interviews and subjective data from 88 respondents, this study ranked 15 project characteristics known to affect project success. Of these 15, five project characteristics were concluded to be the most critical to project success. These were (p.89):

1. Well defined scope,
2. Shared understanding of scope,
3. Owner sophistication,
4. Adequate owner staffing, and
5. Established budget.

It is interesting to recognize that when asked, owners ranked characteristics which are directly controlled by the owners themselves as critical. Also, while characteristics were organized as those affecting success, there was no attempt made to empirically measure their correlation with project performance.

As an extension of Molenaar's work, Songer (1996) polled private and public sector owners to gain a fundamental understanding of attitudes toward the top selection factors identified for choosing design-build. Two goals were to understand why owners were selecting design-build and to directly compare results from private and public sector owners. Of 290 mailed surveys, 182 owners responded. One hundred eight (60%) of these responses were usable. The following factors were cited when owners chose design-build:

1. Shorten duration,
2. Establish cost,
3. Reduce cost,
4. Offer constructability / innovation,
5. Establish schedule,
6. Reduce claims, and
7. Accommodate large project size / complexity.

This research concluded that owners felt very strongly that design-build should be selected to shorten overall project duration. Factors one, two and seven were identical for public and private sector owners. Pooled variance hypothesis testing indicated that six of the seven factors for public and private sector owner's mean rankings were not significantly different. Therefore, despite the differences between public and private delivery strategies and constraints, their attitudes for selecting design-build should be viewed as consistent.

2.2.3 EMPIRICAL PROJECT DELIVERY RESEARCH

Empirical research requires extensive, unbiased performance data from an adequate sample of industry projects. The following research was empirical in nature.

Oberlender and Zeitoun (1993) performed a quantitative study to identify factors known prior to the commencement of construction, which are early warning signs of project cost and schedule growth. A total of 106 US projects collected from 23 CII member companies listed several early warning signs for construction projects and distinguished between fixed price and cost reimbursable contract strategies. This separation was included because fixed priced jobs generally expect fewer changes due to a more defined scope, whereas cost reimbursable jobs are typically awarded prior to the completion of design. Other factors included the selection of bidders via either open bid invitations or the pre-qualification of a group of contractors and price competition measured by 'money left on the table' (MLOT). They also measured the effect of different project delivery types on cost and schedule growth but was unable to correlate these figures with project delivery type due to a small sample. This study represents conclusions about the effect of various factors on project performance. It also documents the negative effect of the 'ripple effect,' a consequence of several successive changes due to a previous change, on project performance. Finally, this research incorporated a data collection method that categorized cost and schedule growth into distinct quartiles of the construction phase. This technique illustrated at which phase certain projects departed from planned budgets and schedules.

Pocock and Liu (1996), used objective performance measures to document differences in four delivery systems used on 209 military projects. Table 2.1 lists the mean values for design-build, design-bid-build, partnering and combinations of these. The authors defined partnering as a "Non-contractual arrangement that changes relationships among owners, contractors, designers, and others on construction projects. It aims to create a team effort, to promote mutually beneficial goals (p. 58)." The combination category was made up of projects utilizing aspects of both partnering and design-build.

Delivery	# of Projects	% Cost Growth	% Schedule Growth
Design-build	90	8.48	27.76
Traditional	40	6.37	26.23
Partnering	63	8.62	17.06
Combination	16	10.44	18.76

Table 2.1: Summary results of delivery system performance (From Pocock and Liu, 1996).

The authors also tracked the number of modifications to the contract and the number of those due directly to design deficiencies. Summary results indicate that no clear distinction can be made between these modifications for all delivery methods. Rather, they show that specific project constraints and characteristics should be considered in combination with the indicators analyzed within this study.

In a more detailed study of the same data, Pocock (1996) developed a method for measuring the impact of project integration on project performance. General comparisons were made using univariate statistical testing such as averages, t-tests, and correlations. Results indicate that each of the alternative methods of delivery possess higher average degrees of team interaction than do traditional projects.

By using specific project data from 16 building projects, Sanvido (1990) identified four critical project success factors. These factors include, "selecting team members with experience; allowing teams to work together using contracts that allocate risk and reward in the correct proportion; developing a team chemistry via common goals and activities; and involving qualified users, contractors and operators early in the design phase to provide optimization information to the team (p. 6-6)." These factors consistently appeared in project delivery literature.

2.3 READING DESIGN AND BUILD FORUM

The University of Reading Design and Build Forum's recent study (referred to as 'The Forum' in this thesis) is the most comprehensive comparison of project delivery systems and the only study based on objective data collected from a large section of the industry (Bennett, Pothecary and Robinson, 1996). The Forum analyzed cost, schedule and quality data taken from design-build and design-bid-build projects recently built in the United Kingdom. The study recognized three distinct variations of design-build and compared them to design-bid-build jobs and projects procured using a management contracting approach.

2.3.1 DELIVERY SYSTEMS

The UK recognized several distinct types of delivery systems. Two were design-bid-build and design and manage. Another three were variations of design-build.

Design-bid-build in the UK represents the common, sequential approach to project delivery where design is completed before engaging the construction contractor. This system and *design and manage,* where the manager holds no construction contracts, are also used in the US. The Forum excluded design and manage from the study since the contractor does not assume any risk for the ultimate performance of the facility.

Traditional design-build was used for approximately twenty percent of new design-build projects. Here, an owner would approach a contractor for early design assistance then negotiate with that contractor for design and construction responsibility. The design-build firm would then acquire outside design assistance or utilize in-house capabilities.

Consultant novation arrangements were used for approximately fifty percent of all new design-build work in the UK. Here, an owner sought independent design advice during the briefing stage from one or more design consultants. Design consultants advanced design to a stage when a contractor was engaged into the process. From this point forward the consultants employment was 'novated' or assigned to the contractor, thus shifting design and construction risk to the selected contractor for the remainder of the project.

Develop and construct accounted for twenty percent of the design-build market. This organizational arrangement differs from traditional design-build only in the extent to which the owner develops design before engaging the construction contractor. Projects varied from owners who had only outline specifications to those having detailed requirements. The owner would then utilize an in-house design staff or appoint a design consultant to further develop these varying levels of design.

Newer approaches to delivering design-build in the UK were using a fee-based management approach. This approach involved a management firm early in the delivery process, but then agreed to a guaranteed maximum price at an appropriate stage.

2.3.2 SUMMARY OF MAIN FINDINGS

Because of the similarity between the efforts completed by The Forum and this study, a meeting was held between The Forum team and this researcher to exchange ideas, discuss procedural techniques and review analysis methods.

The Forum mailed a comprehensive survey to a select sample of owner agents to collect performance data in terms of cost, schedule and quality. Areas of qualitative data describing the project client, management approach, building functions, construction type, size and project location were also collected. The Forum conducted 150 interviews with clients and project team members on a select group of 35 projects. These interviews were conducted to evaluate the accuracy of collected data and to identify differences in project performance. The Forum analyzed 332 projects. One hundred sixty six used design-build approaches, 156 used traditional design-bid-build and 10 used a management approach.

Due to the limited number of projects procured using the management approach, the Forum did not attempt to offer conclusions regarding this arrangement. Therefore, comparisons were limited to project data taken from design-build and design-bid-build jobs. Data showed that design-build projects resulted in:

- a 12% improvement in construction speed,
- a 30% improvement in project delivery speed,
- a 13% reduction in unit cost,
- more certainty in finishing on time,

- a greater chance of finishing within 5% of budget, and
- a higher possibility of achieving specified quality.

In addition to basic univariate comparisons, the Forum conducted multivariate regression analyses to identify variables affecting the performance of certain metrics. To investigate the differences of speed and cost between design-build and design-bid-build, three regression models were developed. *Construction speed* was defined as gross building area divided by the construction time period. *Total speed of delivery*, was defined as gross building area divided by design and construction time periods. *Unit cost,* was defined as project cost per square meter. Each model was based on a reduced sample of project data and explained uneven levels of variation around set response variables. The study did not attempt to develop models for other critical metrics such as cost growth, schedule growth or quality. Therefore, results describing these metrics were based only on univariate comparisons. Table 2.2, orders 11 variables that exerted the greatest influence on construction speed, total speed and unit cost. The table also indicates the number of projects used to build each model and the amount of variation explained by the model.

Regression results indicated that project size, unit cost and facility type are critical to explain speed and cost performance of projects. Delivery system (procurement approach), ranked third in one case, was less important in determining project performance. These findings are important to this study in two primary ways. First, The Forum attempted to measure differences between delivery systems while considering a wide range of variables by using multivariate regression modeling. Second, while explaining only modest levels of variation from a prediction standpoint, these results identified variables other than the chosen delivery method, which are critical to project success.

	Construction Speed	**Delivery Speed**	**Unit Cost**
No. of Projects	223	176	240
Explained Variation	90%	80%	51%
Project size	1	1	5
Building type	2	4	1
Unit cost	3	2	NA
Complexity	4	6	2
Procurement	5	3	4
Technology	6	11	7
Innovation	7	5	8
Building structure	8	10	9
Existence of basements	9	9	10
Quality	10	8	6
Aesthetics	11	7	11
Location	NA	NA	3

Table 2.2: Ordered influence of variables on metrics (From Bennett, et al., 1996)

2.3.3 LIMITATIONS

The procedures, methods and subsequent findings of The Forum's study were limited in several ways. First, there was no indication of the overall respondent population size in the UK building market, therefore it was unknown how representative the collected 332 projects were of the population from which they were drawn. Second, principal metrics of cost and schedule were not analyzed using a multivariate approach. Therefore the effective consideration of a number of identified variables in explaining the differences between design-build and design-bid-build performance was limited. In terms of quality, this study was successful in collecting both intended and achieved quality ratings on sixteen different characteristics. Scores were combined and averaged for comparison. This aggregate procedure may have incorrectly assumed the importance of each question or characteristic as equal.

2.4 SUMMARY OF RELATED LITERATURE

These research findings and the lessons learned from the researchers through discussions with them, have provided valuable background for the data collection instrument and methodology utilized in this research. These initial efforts have established a clear need to expand the direct comparison of systems through a detailed investigation of a large number of projects. It is also evident that several factors have the potential to explain project performance, thus supporting the need for a multivariate analysis. Likewise it is important to recognize that factors are frequently project specific. Variables such as these may act alone in describing performance or may interact with other explanatory variables or the response variables which they attempt to explain.

Studies performed in the area of project delivery have depended largely on survey research and active industry participation. The current state of project delivery research, although not always empirical, identifies numerous variables that have the potential to impact project performance. A collection of these variables were used to develop a framework for this research and a corresponding data collection instrument. These are presented in Chapter Three.

CHAPTER THREE

PROJECT DELIVERY FRAMEWORK

This chapter describes a project delivery research framework, a model for organizing the many factors known to impact project performance. This framework contains eight information categories. These are owner, facility type, project delivery system, procurement method, contract type, facility team, facility and performance metrics. The framework also recognizes the context of an environment in which the facility delivery process exists. Each category contains several variables and potential relationships between them. These categories are defined first in this chapter.

Based on the organization of this framework, this study developed and utilized a data collection instrument to obtain project specific data, which when checked and compiled, could be used to test several project delivery hypotheses. The data collection instrument had to be able to collect factual project data that would allow the researcher to compare seven specific performance metrics for each of the candidate project delivery systems. It also had to provide sufficient project data to accurately identify each project. Finally, the instrument had to collect qualitative data on a collection of variables known to impact project delivery performance. These variables were identified in the literature in Chapter Two and by the taskforce. This chapter also describes the context of that instrument.

3.1 A FRAMEWORK FOR PROJECT DELIVERY RESEARCH

Figure 3.1 illustrates the conceptual framework used in this research. It has been developed to organize measurable variables and potential relationships that are known to impact the facility delivery process. The categories and variables contained in this framework include many areas previously researched and identified in Chapter Two, yet they have not yet been organized into a conceptual model.

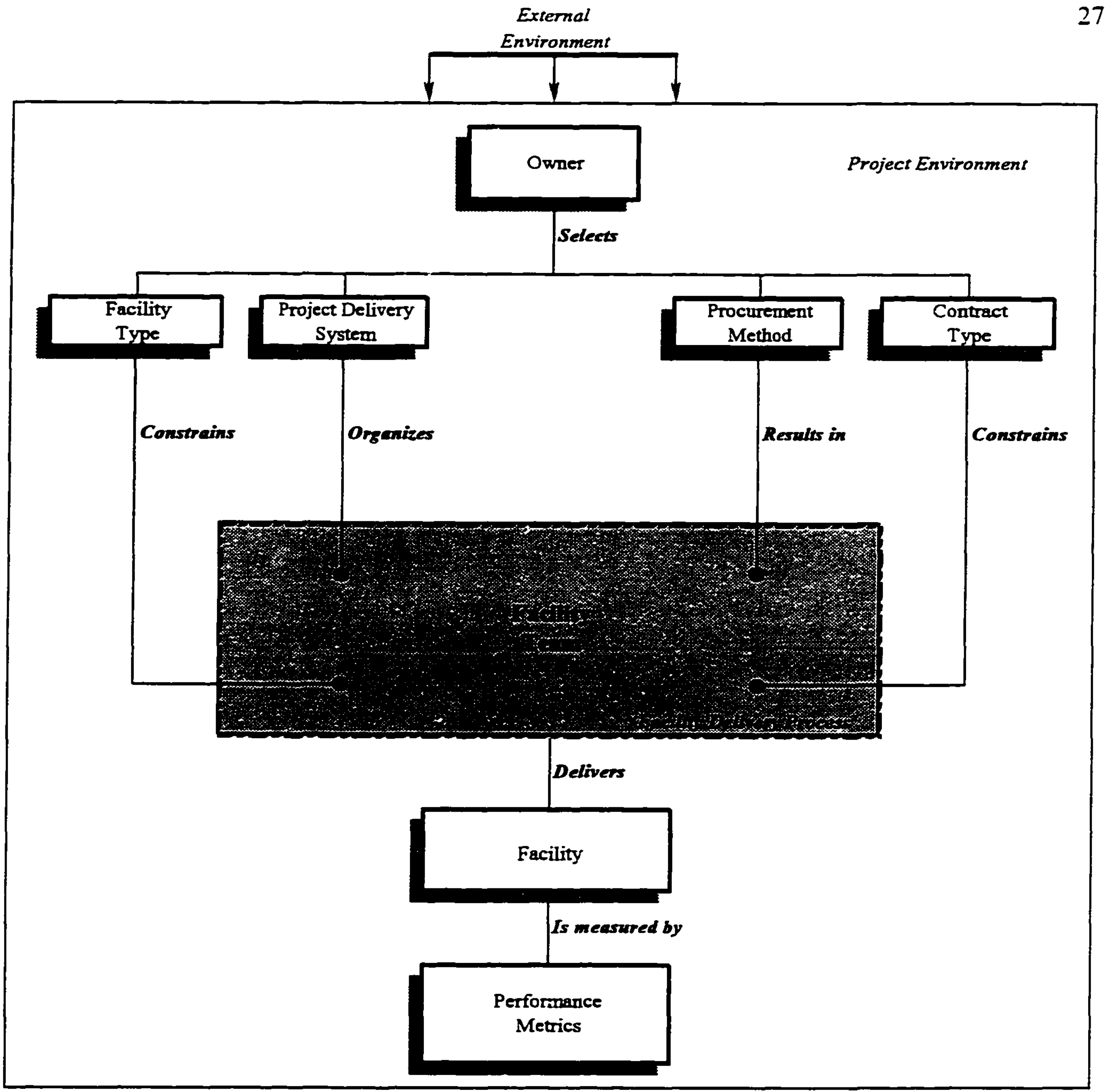

Figure 3.1: Conceptual framework of research variables

The framework shown in Figure 3.1 identifies several key decisions made by the owner which, when executed, impact the development of a facility team. Selections made by the owner define and constrain both the facility team and the facility delivery process in which the team exists. Based on the aggregate collection of these owner decisions, a single facility team is chosen to deliver a facility. The facility delivery process is then measured by several performance metrics.

The relationships contained in this model should be read from top to bottom. For example, an 'owner selects a contract type' and 'contract type constrains the facility team.' Also, the entire framework exists in the context of a project environment which in turn exists within a larger external environment. The following sections define each of these information categories. Key factors that make up this framework are italicized.

3.2 PERFORMANCE METRICS

Seven project performance metrics were used to describe the performance of the facility delivery process. These were the dependent or response variables. These variables were measured after project completion. The following paragraphs define each performance metric.

3.2.1 COST MEASURES

Cost was defined as the investment a facility owner makes in developing a facility and was measured in US dollars. Costs were limited to the design and construction of the facility and did not include land acquisition, extensive site work, process or owner costs. Cost measures included unit cost, project cost growth and intensity (a hybrid of unit cost and schedule measures).

Unit cost, the first metric, was measured to indicate the relative cost of a facility for its given area. It was represented by the formula:

$$\text{Unit Cost (\$/SF)} = [\text{Final Project Cost} / \text{Area}] / \text{Index} \qquad (1)$$

Where:

Final Project Cost was the final design cost plus the final cost of construction. A cost *index* was essential to make accurate comparisons of projects built in different cities in different years. Cost data, with the exception of cost growth (%), were adjusted for time and location using Means 1996 historical cost indexes.

The second metric, *Cost Growth,* provided an indication of the growth of project costs over the life of the job. It was defined by the formula:

$$\text{Cost Growth}(\%) = [(\text{Final Project Cost} - \text{Contract Project Cost}) / \text{Contract Project Cost}] * 100 \quad (2)$$

Where:

Contract Project Cost was the design contract cost plus the construction contract cost.

The final cost metric, *Intensity*, indicated the unit cost of design and construction work put in place in a facility per unit time. It was introduced as a hybrid cost/schedule measure and was defined by the formula:

$$\text{Intensity } ((\$/SF)/\text{Month}) = [(\text{Unit Cost}) / \text{Total Time}] \quad (3)$$

Where:

Total Time was the period from the as built design start date to the as built construction end date.

3.2.2 SCHEDULE MEASURES

Three *schedule* metrics defined the time taken by the facility team and the owner to deliver the facility. Schedule measures included construction speed, delivery speed and schedule growth.

Construction speed was the rate at which the construction team built the facility. It was defined by the formula:

$$\text{Construction Speed (SF/Month)} = [\text{Area} / ((\text{As Built Construction End Date} - \text{As Built Construction Start Date}) / 30)] \tag{4}$$

Delivery speed was the rate at which the project team designed and built the facility. It was defined by the formula:

$$\text{Delivery Speed (SF/Month)} = [\text{Area} / (\text{Total Time} / 30)] \tag{5}$$

Schedule growth was the percentage by which the schedule grew over the life of the project. It was defined by the formula:

$$\text{Schedule Growth (\%)} = [(\text{Total Time} - \text{Total As Planned Time}) / \text{Total}) \text{ As Planned Time}] * 100 \tag{6}$$

Where:

The *Total As Planned Time* was the period from the as planned design start date to the as planned construction end date.

3.2.3 QUALITY MEASURES

Quality was defined as the degree to which the facility met the expected facility requirements. Quality was measured in seven areas. Each was a measure of the actual performance versus the facility user's or owner's expectations of the referenced building. Individual quality scores, based on a maximum of 10, were used for primary univariate comparisons.

The first three quality indices measured the difficulty of the turnover of the facility. It was important to differentiate between poor turnover and poor facility performance. The turnover quality measures included the difficulty of facility startup; the number and magnitude of call backs; and the operation and the maintenance cost for the building/site.

Turnover quality was defined by the formula:

$$\text{Turnover Quality} = Q\text{start up} + Q\text{call backs} + Q\text{operation and maintenance} \qquad (7a)$$

Where:

Qstart up was the difficulty of the facility startup process, *Qcall backs* was the number and magnitude of call backs during the turnover process and *Qoperation and maintenance* was the achievement of expected operation and maintenance costs for the facility/ site. Each of these was scored on a scale of 10. Aggregate scores were used as summary metrics for univariate comparisons. This score combined individual ratings received for facility startup, the number and magnitude of call backs and the operation and maintenance cost scores for the building. A maximum score of 30 was possible for turnover quality.

The next three indices measured specific *system quality*. System quality measures were the performance of the envelope, roof, structure and foundation; the interior space and layout; and environmental systems. System quality measured whether or not these specific systems met, exceeded or did not meet the expectations of the owner and was defined by the formula:

$$\text{System Quality} = Q\text{ersf} + Q\text{is\&lo} + Q\text{environment} \qquad (7b)$$

Where:

Qersf was the quality of the envelope, roof, structure and foundation systems, *Qis&lo* was the quality of the interior space and layout and *Qenvironment* was the quality of environmental systems such as the lighting, heating, ventilating or air conditioning. Each of these was scored on a scale of 10. A maximum score of 30 was possible for system quality.

The last category was process equipment and its layout. Equipment quality was defined by the formula:

Equipment Quality = Qprocess equipment & layout (7c)

Where:

Qprocess equipment & layout was the quality of process equipment if it was included in the facility. Process equipment and layout was based on a maximum score of 10.

This concludes the description of the performance metrics. The factors affecting the delivery of the facility and these resulting metrics are explained next.

3.3 FACTORS

Each of the information categories (Figure 3.1) are described in the following paragraphs. Each category exists in the context of an environment. The project environment is the effect created when all categories of variables interact together.

3.3.1 EXTERNAL ENVIRONMENT

The external environment may impact the context of the project environment. This external environment included four factors. A *qualified pool of contractors* is essential for the accuracy of conceptual estimating. Less qualified firms may not have the experience to estimate projects using schematic designs. Whether or not a qualified pool of contractors exists depends largely on the type of facility being built and the location of the facility. Geographic *location* may constrain the availability of contractors needed for a particular project.

The environment also presents certain *regulatory or legal constraints* that may constrain the owner during the selection process or the facility team during the facility delivery process. Likewise, levels of union and non-union *labor* employed on the job or the amount of subcontracted or direct hire work performed on the project may become a constraint to the facility delivery process. Certain combinations of these four factors may restrict team member performance, hinder the teams' ability to accommodate change, or establish an adversarial atmosphere on the project.

3.3.2 OWNER

Variables describing the facility owner were most important in this research because the owner defines and significantly influences the facility delivery process. Besides selecting facility requirements, delivery systems, procurement methods, contracts or a facility team, the owner organization must consider the impact of several internal characteristics on the project. These characteristics describe the owner's organization .and role in the facility delivery process and are described in the following paragraphs.

Two owner *types* (private and public) were considered in this framework. Private and public owners use different project delivery methods (Songer, 1996, Pocock, 1996). Public owners, including military, local, state and federal governmental agencies, may be restricted in how they assemble project teams. Public owners may be limited by procurement laws which many times require low price selection. They also must consider different funding procedures. In many cases projects may be funded for design first then later for construction. This may lead to large time gaps between when the facility is designed and when construction takes place. Projects may require significant redesign based on differing user requirements, outdated design parameters or cost escalation. Furthermore, projects spanning several years may not benefit from an integrated team experience.

An owner's ability to *restrain the pool of contractors* from which design and construction contractors are selected was also considered (Oberlender, 1993). Owners who buy buildings infrequently may not have the ability or expertise to restrain the number of candidates participating in the procurement process. In much the same way, an owner may not be able to *qualify* candidates based on predefined qualification requirements such as financial stability, backlog, personnel or reputation.

An owner's *ability to define scope* may impact the facility delivery process (Molenaar, 1995). For example, a first time owner can either have a clear, well defined scope of work, or a poor, ill-defined scope of work. Either case may be acceptable if the chosen constructor has the ability to help the owner define the project and the experience to perform the desired scope of work. In addition, the certainty of the facility design and user requirements may dictate how well the job can be estimated.

The owner's *experience with the facility type* also relates to their ability to define scope. One extreme case of this is noticed when a repeat owner, or one that buys buildings frequently, contracts several times with the same firm to design and construct a particular type of facility. Here the owner has good experience with the facility type due to repetition and is likely to have a very well defined scope of work. The design uncertainty is therefore low and the working relationships between the members of the facility team are good. It is expected that this combination would yield low growth in cost or schedule. The key risks in this case are unforeseen or unique characteristics of the site and the local labor supply. On the other hand, a project led by an inexperienced owner, or one who buys buildings infrequently, who is not properly guided by an experienced designer or builder may suffer from poor scope definition. This combination may in turn result in project cost and schedule overruns. These potential relationships support the importance of owners having the ability to define the project scope and choose key team players based on experience, financial strength and reputation rather than price alone.

Experience with the chosen method of delivery is considered separately from facility type experience. Although they may be strongly related, experience with the chosen method of delivery may independently impact project performance. For example, the experienced owner may understand a particular project delivery system. However, uncertainty is introduced when the owner is forced to manage a facility team under an arrangement in which the owner has no experience or knowledge. For example, managing an arrangement which demands teamwork, flexibility and integration may be overwhelming to an owner accustomed to using separate contacts for design and construction services. An owner may be resistant to change, thus decreasing the efficiency of the entire team. Team members may also have a culture suited to a different delivery system. In this case mismatches may cause potential delays or an adversarial context. On the other hand, an owner who is accustomed to working in a team environment may expect more service than is offered in a less integrated system. This in turn may result in cost overruns or liability exposure.

Owners must carefully select a project team of architects and builders that best suit the facility delivery process. Early team interaction can contribute positively to establishing the desired culture under which the team will operate. The *owner's* *relationship with the team* may directly impact procurement, delivery system or contract decisions (Sanvido, et al., 1990). For instance the owner working on a repeat basis with a team may be able to negotiate directly for services rather than develop detailed requirements utilized in pure competitive procurement. On the other hand, with new project teams, relationships must be built throughout the procurement process.

The *capability* of the owner to administer and manage the processes just described may also impact the facility delivery process. For instance, in a design-bid-build mode the owner must be able to administer and manage two separate contracts. This task is reduced to a single contract when using the design-build system. Another example is the *owner's ability to make decisions*. Many factors may affect the decision making process of an owner (Molenaar, 1995). However, many owners do not appoint a lead representative to process and evaluate each inquiry or suggestion made by the facility team. Because of this, the facility delivery process may stall while waiting for a reply or directive from the owner's organization. Therefore, timely decision making has the potential to accelerate the facility delivery process.

The previous paragraphs have identified attributes directly related to the facility owner. The owner's attributes are key influences on their decisions select the facility type, project delivery system, procurement method, contract type and facility team. The next five sections describe these categories in detail.

3.3.3 FACILITY TYPE

Facility type is one variable known at the outset of the project. Six facility types were classified based on building systems, construction type, complexity, experience of team members and final unit cost. Certain facility types behave differently than others in terms of cost and schedule (Bennett, Pothecary and Robinson, 1996). *Complexity* measures the difficulty of designing and constructing certain facility systems. For instance, high technology projects are typically highly complex in terms of environmental or processing systems and generally have intense production and project schedule goals. They frequently sacrifice lower unit costs and low levels of cost growth to achieve more critical production and schedule goals. Flexibility for handling changes and aggressive schedule requirements generally drive high tech projects. On the other hand, light industrial projects such as warehouses, postal and light manufacturing buildings are typically less complex, have large open spans to accommodate processing operations and may employ relatively simple designs on a repetitive basis. These facilities are typically less expensive in terms of unit cost. The researcher expects these types of facilities to have fewer and smaller cost and schedule overruns.

Facility characteristics include the *number of floors* in the building, the construction type, size and specific building systems that further describe the facility. These items are generally known at the outset of the project. For instance, a high number of floors or a multi-story building may require additional planning, for both horizontal and vertical sequencing and for the vertical transportation of personnel and materials. A single story building generally requires extensive horizontal sequence and method planning due to large facility footprints and unconstrained construction sites (Riley, 1994). Multi-story sequences may introduce additional confusion amongst trades and lost time due to poor coordination or construction method changes. However, once patterns are established, multi-story buildings can generally gain efficiencies of repetition not achieved on low rise or single story facilities. In either situation, poor information communication may lead to lost time, contract cost growth or undesirable levels of project quality (Lynch, 1996).

Construction type was defined by new or renovation work. Renovation projects can be potentially costly depending on the validity and accuracy of pre-construction inspections, evaluations and existing contract documents. For example, a contractor may price an interior renovation assuming the structure is usable, however once the walls and ceilings are removed, the contractor may realize the underlying structure has deteriorated requiring either repair or replacement. A project which is almost all renovation has a higher chance of changes than one with only minimal renovations.

The type of renovation may also be critical. A refit of office space including partitions and general lighting is expected to be less costly than connecting floors or buildings, the replacement of load bearing walls or the retrofitting of mechanical and electrical services.

Facility size was considered as the gross building square footage. It was expected that the effect of facility type on project performance depended largely on the size of the project. For instance a very large project may gain certain efficiencies of repetitiveness not experienced on a very small project. Like facility size, facility systems help describe the physical characteristics of the building. Specific systems included *the foundation type, structure type, architectural interior finishes, exterior enclosures, roofing, environment, electrical systems, controls and site characteristics*. The presence of certain system types may impact the facility delivery process in terms of schedule, cost or quality (Bennett, Pothecary and Robinson, 1996). For instance, a caisson type foundation may take more time and be more expensive to construct due to the uncertainty of soil conditions during the drilling process compared to a simple slab on grade system used for the same facility.

3.3.4 PROJECT DELIVERY SYSTEM

This research considered three project delivery systems. These were *design-bid-build*, *design-build* and *construction management at risk*. Each system was defined in detail in section 2.1.1. Each system provides varying levels of team integration. As contracts become integrated, certain efficiencies may occur. These include the improved information communication between team members and lower levels of administrative efforts required by facility owners (Lynch, 1996).

Similarly, levels of uncertainty which surround facility designs may affect facility delivery performance depending on the project delivery system used. For example, a simple office building built several times, may have less uncertainty in its design than a high technology facility being built for the first time. It is expected that the simple office building could be completely designed, void of any constructor input and then built by any one of a number of qualified construction contractors. However, it is unreasonable to expect the same of a high technology facility because of its complex services and systems. Therefore, an arrangement that allows project team members to interact together, early in the design process, may be absolutely necessary depending on the type of facility being delivered (The Collaborative..., 1996). The researcher expects an integrated team on a design-build project to be better equipped to handle complex and aggressively scheduled, technology driven projects than less integrated teams such as ones found on design-bid-build projects.

3.3.5 PROCUREMENT METHOD

Procurement methods range from *open bidding* strategies, based on contract documents, to the *prequalification* of bidders or shortlisting, to *negotiated* or sole source team selection. These various forms of procurement allow the owner the opportunity to select its team based on best value rather than purely low cost (Design-Build, 1996).

The point at which the constructor joins the team, *level of design advancement*, was a significant indicator of facility delivery performance (Sanvido, 1990; Bennett, Pothecary, and Robinson, 1996). Where the constructor joins the team early in design (say between zero and 15% design complete) the team members have the opportunity to develop realistic designs using the experience of each team member. Relationships also develop early on in the project, which may foster the team's ability to handle change and adversity over the life of the job. These characteristics, combined with an earlier and better knowledge of facility design introduce greater certainty in cost estimating.

The other extreme, which engages the constructor very late in the process (say between 90 and 100% design complete) does not benefit from construction input because many of the decisions affecting the design and constructability of the facility have been made. The decisions made early on by the design team may not necessarily be tailored or structured in a way that advantageously uses the expertise or experience of the chosen constructor. Likewise, the constructor is unaware of the history of the design, the purpose of certain details or the overall theme of the project. Information transfer is thus expected to be much slower and may require more information to explain the same scope of work. Owner and architect budgets may then be less accurate due to a lack of price input from the constructor (Design-Build, 1996).

3.3.6 CONTRACT TYPE

The *commercial terms* agreed to between members of facility team and the owner play a role in defining the atmosphere and performance of team members on a job

(Oberlender, 1993). This study considers lump sum, cost plus a fixed or percentage fee and guaranteed maximum price (GMP) commercial terms for each principal team member. Certain contracts restrict the builder or architect to a fixed or lump sum price for a specified amount of work. Reimbursable agreements pay contractors their actual costs but they introduce administrative work for the owner to verify these costs. A GMP contract limits the amount that the owner will pay for the project. In addition, any savings realized by the project team in a GMP contract may be shared or returned in full to the owner. It is expected that project performance is affected by the agreed upon commercial terms.

In the context of the commercial terms agreed upon, contracts may have unfair or *onerous clauses* that constrain facility team members. For example, a contract clause which requires the design-builder to consult with the owner's project manager each time a detail change or scope change is implemented would drastically decrease the productivity of the team. Likewise clauses may be unfairly written which allocate risk and reward disproportionately between facility team members. Thus, depending on the project delivery system selected and the commercial terms agreed upon, it is expected that the presence of onerous contract clauses will impact the facility delivery process (Sanvido, et al., 1990).

3.3.7 FACILITY TEAM

The facility team consists of an architect/engineer and constructor, a design-builder or an architect/engineer and construction manager. These members may then choose to engage other essential team members to complete specific scopes of work. Once key team members are selected, the owner becomes an integral member of the team. The facility delivery process can then be executed by this team. As illustrated in Figure 3.1, several factors impact the creation of the facility team and the subsequent execution of the facility delivery process. Some of these potential relationships have been discussed. Others deal directly with the principal members of the facility team. These are described below.

Selecting team members with experience is known to be a critical project success factor, regardless of the facility type (Sanvido, et al., 1990). *Experience with the chosen* *method of delivery* is considered separately from facility type. Much like the case of the owner the team's experience with the chosen method of delivery may independently impact project performance. Key team members performing for the first time under an arrangement that demands teamwork, flexibility and integration, such as design-build, may be overwhelmed and resistant to change, thus decreasing the efficiency of the entire team. Team members may also have a culture suited to a different delivery system. In this case, mismatches may cause potential delays and adversarial relationships.

On the other hand, key team members who are accustomed to working in a team environment may provide more service than expected in the less integrated system, such as construction management at risk or design-bid-build. This in turn may result in cost overruns or liability exposure. Owners must carefully select a project team of architects and builders that best suit the selected delivery method. Early team interaction can contribute positively to establishing the desired culture under which the team will operate (The Collaborative, 1996).

Experience with the facility type may weigh heavily in a prequalification or selection process where cost alone is not the deciding factor. In addition to the experience each team member has with either the delivery system or facility type, the team may have *significant experience working together*. For instance a construction firm may consistently team with a design firm to respond to design-build proposals. Their experience together on other jobs may positively impact their communication and interaction as a team.

3.3.8 FACILITY DELIVERY

The facility delivery process includes five activities. These are manage, plan, design, construct and operate. Each information category explained above identifies variables which may impact these activities positively or negatively. The owner begins the entire process by making several decisions. Each decision, in combination with the project environment, creates constraints on the facility delivery process. The result of the facility delivery process is the facility itself. Once completed, performance of the process can be measured.

Similar to the experience of key team members with facility types or delivery methods, positive relationships and collaboration can enhance the performance of the project team (Gray, 1989). *Communication* and *chemistry* amongst key team players may impact how they operate and interact during the life of the project. If the same group designs and builds several facilities and establishes a comfortable, trusting relationship, the project stands to benefit from an improved delivery process. The potential for growth in cost or schedule should be minimized due to the team's understanding of how each player operates. Information communication, project administration and cost and schedule certainty should increase with a cooperative, seasoned team. Therefore, extensive partnering or teaming agreements are ways to achieve these beneficial characteristics on a job whose players have never before worked together.

Based on the investigation of the information categories presented in the project delivery research framework, a format for data collection was developed. Variables within each category were organized into a data collection instrument. The specific contents of this instrument are now discussed.

3.4 PROJECT DELIVERY SYSTEM DATA COLLECTION INSTRUMENT

An instrument was developed to collect the data needed to calculate key metrics used to measure the performance of the facility delivery process (Appendix A). Information was organized into nine sections. These categories included the variables described in the project delivery framework (Figure 3.1). The data collection instrument did not organize the variables as they appeared in the framework for two reasons. First, the researcher did not want to bias the data collection process by revealing the relationships described within the framework. Second, the organization of the data collection instrument allowed the respondent to initially complete critical cost, schedule and quality questions and later describe less objective project characteristics. Survey sections one and two provide data to identify the facility and delivery system. Sections three through five contain quantitative and qualitative data describing the key metrics most critical to this study. Sections six through nine allowed the respondent to explain the reasons for measured differences. These sections requested information on variables found in the literature, input from the expert taskforce, and on the relationships discussed in the previous section.

3.4.1 SECTION I: PROJECT CHARACTERISTICS

Of greatest importance to tracking the project were the project name, its location, the respondent who provided the data and the type of organization they were representing. Respondents had to classify their facility into one of fourteen facility categories representing six classes of buildings. Facility classes were light industrial, multi-story dwelling, simple office, complex office, heavy industrial and high technology. Physical characteristics such as the area, number of floors and the percentage of new construction included in the project were also requested.

3.4.2 SECTION II: PROJECT DELIVERY SYSTEM

The respondent was provided definitions for design-bid-build, design-build and construction management at risk and was asked to select the system used on their project. The respondent was also asked to identify the commercial terms used for either the design-builder or for the designer and contractor. Contract types were lump sum, guaranteed maximum price (GMP), cost plus fixed fee, cost plus percentage fee, cost plus GMP and cost plus incentive fee.

3.4.3 SECTION III: PROJECT SCHEDULE PERFORMANCE

Schedule information was collected by asking respondents to list as planned and as built dates for four separate project events. These included the date the project was advertised, the design start or notice to proceed date, the construction start or notice to proceed date and the construction end date, defined by substantial completion. Dates were given in mm/dd/yy format, from which the researcher calculated the duration of each project phase.

3.4.4 SECTION IV: PROJECT COST PERFORMANCE

Budgeted cost, contract award and final cost figures were requested. Contract award amount and final costs were most critical to this study. Contract costs represent the amount agreed upon at the time the contract was signed. Final cost included changes or modifications to the contract. Costs were identified for design, construction and total project costs. In cases where estimated figures were given, owners were contacted to verify the accuracy of estimates. Respondents were asked to deduct items not a cost to the base building, such as, property costs, owner costs, costs of installed process or manufacturing equipment, furnishings and fittings. Respondents were also asked to estimate the cost of site work completed outside the footprint of the building as a percentage of final construction costs.

3.4.5 SECTION V: PROJECT QUALITY PERFORMANCE

Section five was reserved for client input. In each case where the owner was not the initial survey respondent, section five requested a client contact and phone number. Respondents were then instructed to proceed directly to survey section six. The majority of quality data was obtained through phone interviews conducted by the research team. Seven quality questions were asked of each owner. To help reduce potential client bias formed during project turnover, quality data was measured separately for the turnover process and for system performance.

Three questions asked the client to rate the difficulty of the turnover process for startup, the number and magnitude of callbacks and the operation and maintenance cost for the facility. Responses were recorded as low, medium or high. Low represented the best possible rating. Four other questions asked the client to rate whether or not the quality of specific facility systems met, did not meet or exceeded expectations. Literature and expert review identified four systems which represent critical performance and high cost areas of a facility. These included the building envelope, roof, structure and foundations; interior space and layout; environmental systems such as lighting and air conditioning; and where applicable, the quality of process equipment and its layout.

3.4.6 SECTION VI: PROJECT TEAM CHARACTERISTICS

Section six collected data about qualifying and selecting the team, team experience, team dynamics, owner capabilities, and general project constraints. Nineteen characteristics, based on current project delivery literature and input from the CII taskforce, were measured.

First, respondents were asked to record the manner in which the team was selected. Choices included procurement through open bidding procedures, prequalified bidding, negotiated contracting or contract documents. The ability to restrain the contractor selection pool and the existence of a qualified group of contractors was noted. Respondents were also asked to state the percentage of design complete when the construction entity joined the project team.

The second area documented the level of experience held by each team member with similar facilities and with the specific delivery system being reported. Team members included the owner or owner representative, design-builder, architect/designer, contractor and subcontractors. Responses were defined as excellent, limited or no experience with the referenced category. Using the same response choices, respondents were asked to indicate the team's prior experience working together.

Area three focused on team dynamics. Communication and the chemistry between team members were rated as either excellent, limited/adequate or poor/none. The respondent was then asked to rate owners as either public or private. The relationship between the owner and team was tracked as either a first time relationship, a partnering agreement or a repeat arrangement. The fourth area rated factors included the owner's capability, the owner's ability to define the project scope and the owner's ability to make timely decisions. These factors were measured by the respondent as either high, adequate or poor.

Finally, general constraints surrounding the project were reported. The respondent rated project complexity as high, average or low. The presence of regulatory or legal constraints and whether or not the contract included onerous or unfair clauses was also recorded by the respondent. Likewise, levels of union and non-union labor employed on the job and the amount of subcontracted or direct hire work performed on the project were estimated by the respondent.

3.4.7 SECTION VII: PROJECT DATA

Project data more specific than that collected in section one was used to further define facility types. Nine building system categories defined a variety of facility system options and descriptors. Building systems included foundation types, structural systems, architectural interior finishes, exterior enclosures, roofing systems, environmental systems, electrical demands, control systems and site characteristics. Survey respondents were simply asked to check items that applied to the facility or to offer additional information where appropriate.

3.4.8 SECTION VIII: PROJECT SUCCESS CRITERIA

Respondents were asked to list and rate up to five criteria used by their respective organizations to measure-project success. Criteria received a rating of excellent, average or poor. Section eight was one of two sections designed to let the respondent reflect on the outcome and success of the project. The final question asked the respondent to rate the overall success of the project on the same scale.

3.4.9 SECTION IX: LESSONS LEARNED

An opportunity to list lessons learned was included for two reasons. First, it gave the respondent a chance to elaborate on unique project features and to discuss factors which might have affected project performance. Second, it offered the researcher additional information about constraints, relationships and challenges surrounding the project. The respondent listed lessons learned about the project delivery system used and why they thought the project could have been better delivered or more successful. Respondents were probed about their experience using the described system by asking them directly whether the delivery system enhanced or hindered their ability to perform. The respondent completed the questionnaire by stating whether the project met the intended needs and by describing unique project features that may have influenced its cost, schedule or quality.

3.5 SUMMARY

Literature, related studies and expert collaboration have guided the development of a tool to collect objective data from the industry. Lessons learned from previous studies and other researchers indicated principal areas where performance measurement was needed, thus shaping the creation of seven key metrics. Methods used to collect, check and analyze collected data is the subject of Chapter Four.

CHAPTER FOUR

DATA COLLECTION AND ANALYSIS METHODS

The purpose of this research study was to empirically compare cost, schedule and quality performance of projects delivered using construction management at risk, design-build and design-bid-build delivery systems. An empirical research method that recognized the lessons learned from other researchers who have pursued similar objectives (Bennett, 1996, Oberlender, 1993, Pocock, 1996) was used. This research used only quantitative and qualitative project data gathered by first hand observation, either by the researcher or by someone else (Simon, 1985). This research used a structured data collection instrument to collect project specific data. It did not consider anecdotal evidence or opinions. The following paragraphs explain the effective use of survey research in the construction arena and techniques that were implemented to increase the validity and reliability of collected data.

4.1 DATA COLLECTION METHOD

Two possibilities exist to collect project related information from the industry. One uses opinion polls to document perceptions of project performance. The second, which was used for this research, collects project facts directly from project participants. Data can be collected through a structured interview or through the use of a structured questionnaire (Simon, 1985).

The geographic distribution of respondents, the dispersion of respondents across various organizations and the vast number of respondents prohibited the sole use of face to face interviews. Therefore a structured questionnaire, used in combination with follow-up telephone interviews, targeted a reachable sample of industry respondents. This procedure allowed the researcher to contact a greater number of the respondent population at a significantly lower cost. Furthermore the ability to stratify and sort by subcategories was critical to the comparison of delivery systems and required a substantial sample size.

4.1.1 SURVEY PROCEDURE

One of the weakest areas of data collection is the researcher's inability to plan and execute a specific procedure that is critical for maximizing response (Dillman, 1978). Research on mail data collection suggests that to maximize response rate, each aspect of a research effort should be designed and implemented in a way that transmits the most positive image (Tanur, 1984). Of 16 techniques listed to improve the quantity and quality of mail responses, this study successfully implemented 12. These techniques included the design of an attractive, short questionnaire, the inclusion of postage paid, return envelopes, official sponsorship, anonymity and confidentiality, the use of timely follow-ups by mail, telephone and fax and the offering of incentives such as research results.

4.1.2 DATA COLLECTION AND FOLLOW-UP

The following procedures were employed during the final phase of collection and follow-up. First the researcher organized a five member team to collect data responses. Each team member was familiar with the objectives of this research and was aware of the terms and information contained in the data collection instrument. Standard fax forms and telephone dialogue were developed to increase the consistency of the collection effort and to maintain the professional image portrayed through the survey. Team members worked side by side in the same office. This allowed the data collection team to customize and regulate the approach to collecting follow-up data. Project data was obtained by mail or fax. Faxed responses were generally followed by mailed copies of the data. Each response was given a project reference number to maintain respondent confidentiality. Once recorded, each response was traced to its affiliated organization through an alphabetical code unknown to the respondent. This procedure allowed the researcher to track the number of responses submitted by each industry organization, thus eliminating a major portion of respondent bias.

4.2 DATA VERIFICATION

Data was collected by mail, fax, telephone interviews and by 12 face to face interviews conducted during two site visits. Because of these distinctly different modes of collection and the nature of data being pursued, checking the accuracy of data was critical. Each project response was reviewed upon its receipt. Critical areas for checking included whether or not the project met the scope of the study in terms of the facility type, its substantial completion date and its defined delivery system. Several projects deemed inappropriate were excluded from the analyzed sample. These included single family homes, two cemetery expansions and projects delivered under an agency arrangement. More detailed efforts to check cost, schedule and quality data required follow up phone interviews. Due to certain levels of item non-response,[1] each respondent was telephoned to verify project facts and to complete missing information. On average, four calls to various project team members were placed to thoroughly complete project data. In every case where the respondent was not the owner, the owner was contacted directly to collect project quality data. The researcher also obtained a second check on project cost and schedule data submitted by the original respondent by asking clients to verify this data.

Extensive checking of project dates, costs and quality performance ensured the accuracy and standardization of the collected data. Interacting with survey respondents offered the researcher the opportunity to discuss lessons learned on the job and understand reasons why projects may have performed as they did. Conversations with owners offered a valuable perspective on how the delivery system had performed. This perspective described more fully the nature and fundamental characteristics of each project.

4.3 RECORDING DATA

A project tracking database was developed to record specific respondent information such as owner and project participant names, affiliations and addresses. This confidential information was used by the researcher to maintain contact with project respondents during data collection, to analyze the distribution of samples for the non-response study and to disseminate survey results.

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[1] Item non response occurs when a respondent's answers to some parts of a survey are missing or inconsistent (Tanur, 1984). For example, when a final project cost is reported less than the sum of final design and construction costs, an error may be present. Another example occurs when certain quality questions such as those evaluating process equipment are omitted due the nature of the facility.

Data from 351 projects were entered into a spreadsheet using a numerical coding system for each possible response to each question. Data such as project locations, project size, performance dates, and cost figures were entered directly as they appeared on the survey. Each project response was entered three times by different members of the research team. Each iteration was matched to the previous and to the original survey to check for errors. An additional check was made of principal metric values by investigating the outlying or abnormal values. These data points were reconciled where appropriate.

Once project data was properly coded for analysis it was exported from the spreadsheet into a Minitab® statistical software package. Minitab® was chosen because of its significant power in processing a very large number of variables and its extensive sorting capability. The spreadsheet software package was used only for data storage and basic metric calculations.

4.4 NON-RESPONSE STUDY

Inherent in all survey research efforts is the potential for a lack of participation from respondents who make up the population investigated by the research. It is evident from studies related to construction research that efforts made to adjust for non-response are not performed. Investigating non-response was a principal step used in the verification of data in this study.

Sampling has provided a sound method for taking a random sample from a population, determining a statistic about that sample and then describing that statistic as a parameter for the entire population. However, in cases of low respondent participation, it becomes difficult to conclude whether or not a statistic is representative of an entire population. In such cases it is extremely helpful to obtain additional information from another sample of the population. This allows the researcher to compare the original sample against the secondary sample to validate the assumptions being made about the population as a whole. This effort is referred to as a study of non-response.

Studies as large as the US census have suffered from a lack of respondent participation or non-response (Tanur, 1984). It is common for levels of non-response to range from a low of 5 percent to a high of eighty seven percent. Tanur explains that without significant efforts to curb obvious non-response or to explain it through the use of proven techniques, a study suffering from a low response rate will become practically and scientifically useless. Therefore, the researcher performed a non-response study to explain and adjust for low respondent participation.

4.4.1 NON-RESPONSE SAMPLING

A survey is performed by taking a random sample of a population. This sample may represent only a portion of the population. A portion of that population will respond, say forty percent. The remaining sixty percent of the population represents the amount of population who can be classified as non-respondents. The goal of the non-response study is to obtain a sample from this sixty percent to explain the reasons for their non-response. The researcher can then test for differences between the newly obtained sample and the original sample.

The non-response sample is limited to those respondents who did not originally respond to the survey and is calculated by taking the inverse of sample categories previously used. For instance if one hundred surveys were received as a result of the first mailing, and seventy percent of these one hundred responses were obtained from a single group of respondents, then only thirty percent of the non-response sample surveys should be mailed to members of this group (Handcock, 1997). This inverse distribution of sample size ensures proper coverage of respondent type and affiliation while limiting the amount of duplication or overlap.

4.4.2 NON-RESPONSE SURVEY ADMINISTRATION

Individuals who choose not to respond to an initial survey can be encouraged to respond through a second sampling. Successful techniques to foster this participation include callbacks, establishing rapport with respondents or convincing respondents of the importance of their participation. However, utilizing extreme efforts to obtain data can negatively affect the validity of the research. For instance, several elusive respondents may be reached with increased efforts or repetitive questioning and their responses will certainly improve response rates. However, a respondent who is pressured into responding may indeed improve response but at the expense of valid data. An approach that includes quality data at a high response rate must be developed.

A non-response cover letter accompanied the second survey. The letter explained the purpose of the second data collection effort and encouraged each respondent to help advance research in this area by participating. The identical survey used during the initial data collection phase was used for the second phase. A phone call to each respondent was placed prior to and shortly after the mailing of non-response surveys. This informed the respondent that the survey request was coming and verified the receipt of the survey packet. Survey packets, sent using first class and express mail service, included a cover letter addressed to the specific respondent, one survey and a postage paid envelope. The researcher and one member of the original research team contacted each respondent on several occasions. This process helped clarify respondent questions and encouraged those less motivated to reply. The non-response data collection effort was completed in two months and collected data from an additional 50 projects.

4.4.3 EXPLAINING NON-RESPONSE

Substantial data about a random sample of non-respondents will indicate one of two positions (Tanur, 1984). The first is that the forces preventing some people from responding are unrelated to the variables of interest, thus indicating that results are representative of the original sample from which they were drawn. A second position is that the forces preventing some people from responding are directly related to the key variables the study is trying to measure. This means that the individual's project/data is substantially different from the sample. If in fact these forces are related, the results are biased and the study must report those characteristics causing the bias. An example of bias follows.

An individual, when asked why he/she did not respond to a survey, simply states, "I did not have time." In the case of construction project data, it is important to know whether or not a respondent did not have time due to an increased work load or due to other reasons which may have affected the variables in question, such as a disorganized workplace or an inability to make decisions in a timely fashion. Therefore, using project data, the researcher can investigate reasons for non-response and test for differences by analyzing the performance metrics of a project submitted by this individual versus that of an original respondent.

4.5 DATA ANALYSIS

The analysis of project data utilized several statistical methods. Univariate analysis included the comparison of central tendency measures such means, medians and deviations. Multivariate analysis used a more detailed process of explaining variation surrounding certain critical variables. Both methods were important to this study and were chosen based on the need to evaluate such a large sample of data. Nearly seventy response and explanatory variables allowed for meaningful comparisons. The following paragraphs represent methods used to analyze specific project data.

4.5.1 UNIVARIATE COMPARISONS

Understanding data sets and larger samples is a basic principal in statistical analysis and requires several steps (Voelker, 1993). Descriptive statistics offer ways to measure the central tendency of a large data set. Measures such as the mean, median, variance and ranges of several metrics calculated from project data were used as initial comparisons. However, the common statistical assumption of normally distributed samples was clearly inappropriate. The initial analysis of central tendency quickly confirmed that mean, median and mode values were very different, thus indicating the need for a battery of tests. Therefore, detailed hypothesis testing was required to make conclusions about the significance of differences between delivery system performance.

Hypothesis testing measured the strength of evidence in the data for or against precise statements about population characteristics. The first hypothesis testing used two sample t-tests based on sample means. For example, the tests used to compare delivery systems in terms of cost growth, indicated the level of significance with which the researcher could claim one delivery system was performing differently than another. Hypothesis testing for sample medians was also chosen. Mood's median test was used because it effectively adjusts for outliers in data, and is particularly appropriate in the preliminary stages of analysis (Minitab, 1995). Working together, two sample t-tests and Mood's median tests allowed the researcher to test significance between a number of critical metrics.

4.5.2 MULTIVARIATE LINEAR REGRESSION MODELING

Exploring univariate comparisons offered direct conclusions about specific categories such as delivery system, facility type or client type. These comparisons were limited to a select group of principal variables and thus, were unadjusted for the many other variables known to affect project performance.

A great number of variables may affect project delivery performance together or on a project specific basis. Several examples of these predictor variables were described by the literature and included facility area, facility type, delivery system, owner type or the commercial terms agreed upon by facility team members. Multivariate linear regression[2] was used to quantify the measured differences between the key characteristics of cost and schedule (Neter, 1996). This process adjusted for the affect of delivery method while holding all other variables fixed.

The development of several models for each variable of cost and schedule identified the tendencies and the quantity of variation being explained by the data. Multivariate regression models were developed for several principal metrics. These models are explained with varying levels of certainty for direct, multivariate comparisons between project delivery systems. Variables included in each model were rank ordered. Steps to build multivariate linear regression models used in this research follow.

1. Identify the entire set of discrete, continuous and indicator variables described in the project delivery framework.
2. Develop a 'best sub-set' regression model using all possible variables.
3. Choose an initial model from the 'best sub-set' using the best combination of high explained variation, and low Mallow's C-p value. (Neter, 1996, p.341)
4. Investigate variables identified by 'best sub-set' algorithms.
5. Calculate multivariate regression model to investigate residual model diagnostics.

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[2] The term regression is used to describe statistical relations between variables (Neter, 1996).

6. Identify all 'unusual observations' and explain their reasons for being unique.
7. Develop a list of variables which consistently affect those observations with great or poor performance of the chosen performance metric. (For example, in the analysis of construction speed, the variables low complexity, facility type, good communication, quick decisions, repeat process, and aggressive schedules consistently affect performance.)
8. Calculate multivariate regression model with highly unusual or explained outliers removed.
9. Evaluate the residual model diagnostics.
10. Check relationships between each individual variable used within the model and the residual values generated from the regression.
11. Develop transformations on those variables whose relationships appear non-linear.
12. Calculate the multivariate regression model again, tracking any improvement to the explained variation as a result of variable transformations.
13. Evaluate the residual model diagnostics.
14. Explain the meaning of all new, transformed variables. (For example, log, inverse log, root, or inverse.)
15. Develop all potential interaction effects.
16. Calculate the multivariate regression model again, tracking any improvement to the explained variation as a result of developing and including interaction variables.
17. Evaluate the residual model diagnostics.
18. Perform tests of leverage and influence, identifying those observations which greatly affect the models' ability to track the data. Explain these observations.
19. Calculate the multivariate regression model again, tracking any improvement to the explained variation.
20. Evaluate the residual model diagnostics.
21. Continue these activities until reaching the desired level of explained variation, independent variable significance, and the significance of the chosen variables as a group. (For example, p-values, t-values, F-statistics, Anova tables, etc.)

4.6 DATA QUALITY

Several methods were used to reduce potential areas of bias. These methods helped reduce respondent bias, non-response bias and bias introduced by the research team.

4.6.1 RESPONDENT BIAS

Respondent bias represented the level of subjectivity which entered an individual's response. This study collected cost, schedule and quality values which represent valid, objective data. However, other areas such as team characteristics and lessons learned required the respondent to rate or list that factor on the project.

It was also imperative to eliminate bias surrounding the defined delivery systems being investigated by the study. The researcher targeted several sources for project data and noted those which may have been biased toward certain delivery methods. A coded tracking system, unknown to the respondent, was utilized on each survey form. This code allowed the researcher to measure the number of responses being submitted by a single group or national organization. Results indicated that an unbiased distribution of projects was obtained from each organization both in the original sampling and in the non-response effort.

4.6.2 NON-RESPONSE BIAS

Non-response data represents a sample of projects used to determine whether collected data is valid and representative of the population from which it was drawn. The proportion of respondents that were unreachable, out of business or out of the project scope was tracked during the non-response study. This allowed the researcher to infer, with greater accuracy, the number of respondents who were likely not appropriate for the original sampling. For instance, based on the initial data collection effort, results indicated that just over six percent of the population was inappropriate or out of the research scope. However, based on the efforts of a much smaller non-response sample, results indicated that in fact nearly 29 percent of the population might be inappropriate for inclusion in the study. This finding offers a significant advantage to this study as well as future studies, by indicating the relative proportion of the population that was suitable for participation. In other words, future studies, with similar scope, objectives and methods, can expect that a value closer to 30 percent, rather than six percent, represents the proportion of the sample size which might be inappropriate for participation.

Data obtained from the non-response study was tested to ensure that it was statistically similar to data collected from the original sampling. Significant bias was eliminated by testing for differences between the two samples. The subsequent combining of these samples into one large group was contingent upon statistical test results.

4.6.3 RESEARCH TEAM BIAS

The researcher organized a team of researchers to collect, track and input project data. Each member, although trained in the construction field, had no preference toward any delivery system or other project specific data. Training sessions, standardized data collection activities and the proximity of research team members to this researcher helped improve consistency and remove research team bias.

Data analysis efforts were conducted by the researcher. Results were presented to and reviewed with the taskforce and thesis committee members at several stages of their evolution. This helped to clarify findings, to raise questions best answered by members of the industry and to diminish the chance of the principal researcher being mislead by unusual data. The researcher exhibited no bias toward the delivery systems investigated in this study primarily due to a lack of extensive experience using each method.

4.7 SUMMARY

Methods to collect objective project data directly from the US construction industry were reviewed. The application of proven methods was important to ensure adequate response. Several techniques used to verify, check and analyze collected data were also described. Techniques such as checking project facts with multiple project respondents and performing a non-response study, were critical components of this research and greatly improved the validity of research results. Finally, the quality of data used in this research effort was discussed.

CHAPTER FIVE

DATA STANDARDIZATION

Chapter Five begins with a discussion of survey response rates and describes the reasons why industry members chose not to participate in this research. The statistical testing required to combine non-response and original samples is presented. Data adjustments such as the classification of facility types, the standardization of data points and cost indexing are then described.

5.1 RESPONSE RATES

Response rate is the ratio of survey respondents who actively participated in the survey to the number of respondents actually reached through the survey. Specific rates for the original data collection process and for the non-response collection are described below.

5.1.1 STUDY RESPONSE RATE

Project delivery system surveys were mailed to 7600 respondents from a variety of organizations. Of these, 174 surveys did not reach their destination due to incorrect addresses. A total of 378 survey responses were completed and returned. Thus, a response rate of 5.1 percent was achieved during the original data collection effort. Fifty international projects and 27 US projects which were either not completely constructed or which were out of scope, were inappropriate for analysis. Therefore, data from 301 projects collected in phase one were usable for analysis.

5.1.2 NON-RESPONSE STUDY RESPONSE RATE

Eighty non-respondents of the original survey were targeted for data collection and analysis. After responses were obtained from these 80 non-respondents, twenty three were inappropriate or out of the scope of this study. A total of 54 survey responses were obtained during this collection phase, representing a response rate of 94.7 percent. Of the 54 projects, two were not substantially complete and two were out of the scope of the study. Therefore, data from 50 projects collected in this phase was usable for analysis.

5.2 REASONS FOR NON-RESPONSE

People cited several situations and reasons why they chose not to participate in this research. These reasons follow.

5.2.1 PROJECTS OUTSIDE OF SCOPE

Several companies had projects that did not fall within the scope of this research. These respondents worked for firms whose core business fell outside the general building sector of the US construction market.

5.2.2 NO FOLLOW-UP POSSIBLE

Several organizations had policies that forbade telephone follow-up once a survey packet was received. The research team contacted a small number of these respondents by phone to verify whether people had received the information.

5.2.3 SURVEY FORWARDED TO NEW RESPONDENT

In several cases an individual had received the survey packet, but was unable to respond either due to time or because specific information was archived in a different location. In an effort to assist the research effort, the respondent forwarded the survey packet to another person within their firm. In a few cases, the second contact again forwarded the information to someone in another division, such as a technology or building division where more representative projects existed. The research team followed these trails to obtain project data. This scenario was frequent with CII member companies who regularly transfer the role of data liaison between different people within the company.

Another example occurred when corporate presidents forwarded the survey to an employee within their company or worked jointly with a project manager or superintendent in providing data from a specific project. Therefore a company representative was the replacement for the original respondent.

5.2.4 COMPANY OUT OF BUSINESS

The researcher discovered instances where firms had gone out of business. These respondents were classified as non-participants, or were placed in the category of firms who never received the survey. To verify this possibility, the researcher reported the status of the company to the lead representative from the national organization from which respondent information was obtained. The representative then checked with their national membership department and confirmed the researcher's finding.

5.2.5 DATA COLLECTION INSTRUMENT NEVER RECEIVED

The number of respondents targeted in both collection efforts was less than the original counts of 7600 and 80 for several reasons. These include incorrect respondent addresses obtained from national organizations and misplaced survey packets within an organization prior to them reaching the respondent. In several cases the researcher was unable to contact certain respondents directly to verify in each case that survey packets had been received. In another case a respondent had left the company, and the package was thrown away.

5.2.6 RESPONDENT NOT INTERESTED IN RESEARCH

In some cases the initial individual received the survey packet, however, it became clear through the phone interview that they were genuinely disinterested or disgusted with surveys and had absolutely no intention of participating. Few of these situations occurred, and in each case the respondent either phoned or sent notice by email that they would not be participating.

5.2.7 RESPONDENT HAD NO TIME

Finally, the most frequent reason for non-response was a lack of time to complete the survey. This type of respondent was very important to the data collection effort. These people, although they understood the importance of the research, simply could not spend the time to participate. Naturally, a number of people were unable to help the research effort. However, a greater number of these respondent types were convinced by the researcher to take the time to participate. The researcher helped these respondents by answering questions regarding the requested information or by collecting data directly during the phone interview. In other cases, the researcher obtained limited information and several points of contact for other project players who were able to assist the effort by participating.

In several cases, respondents said that they had many surveys to complete and were willing to help, but they were trying to run a business at the same time. One example is from an individual who had five research surveys to complete. This researcher's request was the last received and the respondent planned to complete each of them in the order that they were received. In this case it was inappropriate to continuously phone the respondent when it became clear that their work load was restricting a timely response.

5.3 DATA ADJUSTMENTS

Before the data could be analyzed as a whole, adjustments had to be made. These were cost indexing and the classification of facilities.

5.3.1 COST INDEXING

Cost data was collected for the design and construction of building projects. To standardize data across the entire sample, each project was adjusted using historical cost indices (R.S. Means, 1995). Unit cost, and intensity measures were two metrics affected by this standardization. Indexing was necessary for the direct comparison of projects built in different locations during different years.

5.3.2 FACILITY CLASSIFICATION TECHNIQUES

Projects were initially drawn from four broad facility classes: private general buildings, light industrial, technology projects, and parking decks. Initial testing indicated a large variation between projects within each class. For instance, class one, private general buildings, had 140 projects in its class, a median[1] cost growth of 4.42 percent and a standard deviation of 105.99. This large variation within a single facility class prompted the researcher to develop a formal project classification scheme using variables such as building systems, construction type, complexity and final cost per square foot. This process more closely categorized like buildings into six classes. As a result, projects from class one above, were divided into two separate classes. The first of the two new classes had 65 projects, a median cost growth of 2.79 percent and a much lower standard deviation of 10.68. The second of the two new classes had 54 projects in its class, a median cost growth of 2.57 percent and a standard deviation of 7.06. The remaining 21 projects from the original facility class of 140 projects were moved into other classes which were more alike. The building classification process is outlined below.

A master database of all surveyed projects allowed the researcher to easily identify projects within each broad class whose cost and/or schedule performance were extreme outliers. These projects indicated the number and distribution of unusual or outlying projects found within each broad class and thus served as a starting point for the reclassification of all projects. Data from outlying projects were checked to ensure proper data input and to verify the accuracy of figures and metrics calculated from the original survey. Once outlying projects were reconciled, the researcher examined each original survey to check the following items as noted by the respondent:

- relative experience of the project members with similar facilities as well as their relative experience with the same delivery system,
- degree of project complexity whether high, average or low, cross referenced against the relative experience of the members above,
  For example, a respondent who had extensive experience with a particular facility type may have rated the complexity of such a job as low, whereas a respondent

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[1] For all 351 projects the mean cost growth was 5.92 % and the median cost growth was 3.08%. This difference is small. However, for smaller data sets, such as sorts investigating delivery type, the average or mean value can misrepresent the data. For instance, if just four or five of the 155 design-build jobs are above 40% cost growth and the others are all below or near zero, the average will misrepresent the sample. A median value is the mid point of a ranked data set and prevents the abnormal distribution of a data set that can occur when a few projects have a high or low cost growth. Therefore, median values are used throughout this research.

with limited or no experience with this facility type would tend to rate complexity as high.

- degree of legal constraints whether many, few or none,
- project data for each of the project's building systems to clarify the complexity of building structure and enclosure, amount and detail of interior architectural finishes, extent of electrical and mechanical loads, and site conditions,
  For example, a low complexity project might be a pre-engineered metal building with minimal interior finishes and some office spaces that require basic environmental and electrical equipment and controls. Intensive computer use and complex mechanical loads might indicate a more complex project for both design and construction.
- lessons learned, which identified whether any unique features or management decisions impacted the project's cost, schedule or quality outcome, and
- the actual unit cost of the project calculated from the data, cross referenced against the other projects reported within the same facility class.

5.3.3 FACILITY CLASSES

As a result of this process, six facility classes of similar projects based on their building systems were developed. Each class is described below.

Facility type one, *light industrial*, includes warehouses and storage facilities, light manufacturing and postal facilities and basic civil structures. Warehouses and storage facilities generally had a simple building structure and envelope with minimal electrical and mechanical loads. Light manufacturing plants also had simple building structures and envelopes but may include associated office spaces and control rooms requiring process equipment with minimal environmental control. Postal facilities were typically large facilities with enclosed processing areas and heavy electrical and mechanical controls. Civil facilities such as mass transit stations, parking decks or pedestrian mezzanines had large open air spaces, minimal lighting requirements and few mechanical loads.

Facility type two, *multi-story dwelling*, included residential complexes characterized by low-rise and multi-story dwellings such as hotels with repetitive units. Type two also includes on-base military housing such as bachelor's enlisted quarters and dormitories.

Facility type three, *simple office*, included schools and recreational facilities characterized by large, multi-purpose and mixed use spaces for congregating, dining and exercising. Family three also includes office buildings requiring basic, general lighting, light computer use and flexible interior layouts such as open office environments and training rooms.

Facility type four, *complex office*, included offices and buildings with monumental finishes. Complex offices generally exhibit intensive computer and environmental loads such as corporate offices, data centers and clinical medical offices. Buildings with monumental finishes such as embassies, courtrooms, libraries and archive facilities, typically display elaborate architectural finishes and stipulate strict security requirements.

Facility type five, *heavy industrial*, included large facilities with enclosed processing or refrigeration areas and intense electrical and mechanical controls like those required in food processing plants. Heavy manufacturing facilities usually had significant process equipment loads and required strict environmental compliance.

Facility type six, *high technology*, included micro-electronic and pharmaceutical clean room facilities, hospitals and research and development environments such as surgical clean rooms and support offices requiring strict environmental control. Also included in class six were petro-chemical facilities which generally included extensive process piping, heavy mechanical loads to support equipment and large open spaces to accommodate vessels and tanks.

5.4 COMBINING SAMPLES

The ability to combine data from samples collected at different times was contingent upon characteristics of each sample. Therefore, both the original sample of 301 projects and the non-response sample of 50 projects were analyzed and tested. The purpose of this exercise was to verify whether project data received from survey non-respondents was significantly different, in terms of key performance metrics, than the original sample. This was accomplished by performing two sample t-tests and Mood's median tests for sample means and medians at a confidence level of 95%.

Table 5.1, Two sample t-test results of original and non-response sample means and Table 5.2, Mood's median test results of original and non-response sample medians illustrate that the samples are similar.

Two sample t-tests	Sample Size		Critical T-Value	Test Statistic	P Value	Equal
Metric	Original	Non-response				
Unit Cost	301	50	1.676	0.29	0.39	Yes
Cost Growth	301	50	1.676	-0.47	0.32	Yes
Schedule Growth	301	50	1.676	-0.45	0.33	Yes
Construction Speed	296	50	1.676	-1.36	0.09	Yes
Delivery Speed	301	50	1.676	-0.3	0.38	Yes
Intensity	301	50	1.676	-0.08	0.47	Yes

Table 5.1: Two sample t-test results of original and non-response sample means.

Table 5.1 indicates that in no case were the mean values of either sample significantly less than or greater than the other. The critical T-value was obtained from statistical tables and was based on the size of the samples being compared, the standard deviation of each sample, the mean of each sample and a 95% level of confidence for which tests were being conducted. This table value was compared to the test statistic calculated from the samples. Significance was indicated when the value of the test statistic was greater than the tabled value. Thus, Table 5.1 shows that there was not enough evidence to support the hypothesis that one sample mean was less than or greater than the other, therefore, the alternative hypothesis of equal sample means was supported.

Table 5.2 indicated a similar result by testing the sample medians. This test used a critical Chi-squared value of 5.99 which represented a level of confidence of 95%.

Sample medians for each metric were tested and individual Chi-squared values were calculated. Significance was indicated when calculated Chi-squared values were greater than the critical value of 5.99. Thus, Table 5.2 shows that there was not enough evidence to support the hypothesis that one sample median was different from the other, therefore, the alternative hypothesis of equal medians was supported.

Mood's Median Tests	Original Median	Non-response Median	Test Values		
			Chi-Square	P	Significant difference?
Unit Cost	102	107.5	0.4	0.527	No
Cost Growth	3.3	0.74	1.44	0.23	No
Schedule Growth	0	0	0.08	0.776	No
Construction Speed	7874	6776	0.35	0.556	No
Delivery Speed	4754	4435	0.35	0.556	No
Intensity	4.43	6.05	2.4	0.121	No

Table 5.2: Mood's median test results of original and non-response sample medians.

Each of the seven measures of quality were also analyzed using two sample t-tests in the same manner. Tests for sample means were most appropriate for quality because scores were reported on a fixed scale from zero to 10, thus eliminating the chance of highly unusual or outlying scores misrepresenting the central tendency of the samples. Results for quality metrics indicated no significant difference between samples. Therefore, samples were combined for further analysis. This analysis indicated that the sample of projects collected were representative of the industry population from which they were drawn, thus allowing the researcher to describe industry performance using the results obtained from the analysis of 351 projects.

5.5 SUMMARY

Data from 351 projects were used in the analysis of this research. Although just five percent of the population was surveyed, the significance in the size of the sample of projects obtained and the success of the non-response survey added validity to the forthcoming results. Chapter Five also made several data adjustments such as the classification of facility types and project cost indexing.

CHAPTER SIX

RESULTS

This chapter presents the results of the detailed statistical analysis of project data in three parts. First, the data sets defining sample distributions by facility type, delivery system, owner type, project size and project cost are presented. Second, univariate results are reported. These describe basic relationships between delivery systems, facility types and client types unadjusted for the many other variables that surround project performance. Third, a multivariate analysis discusses results in more detail by offering conclusions and direct comparisons between delivery systems after adjusting for all variables measured in this research. Regression results indicate the levels of uncertainty which surround the conclusions presented about each performance metric. Finally, those variables that accounted for the greatest proportion of variation are rank ordered.

6.1 DATA SETS

Of the 351 projects surveyed, 23% were delivered using construction management at risk, 33% used design-bid-build and 44% were design-build. The sample was unbiased toward any of the three project delivery systems.

Six facility types were classified as light industrial, mult-story dwelling, simple office, complex office, heavy industrial and high technology. The distribution of projects by individual facility type ranged from a high of 25% in light industrial, to a low of 5% in heavy industrial. Figure 6.1 represents the proportion of the entire sample in each facility type. Although the heavy industrial group was least represented with 17 projects, the large size of the entire sample and various statistical tests which accounted for individual sample size allowed the researcher to make meaningful conclusions about this facility type.

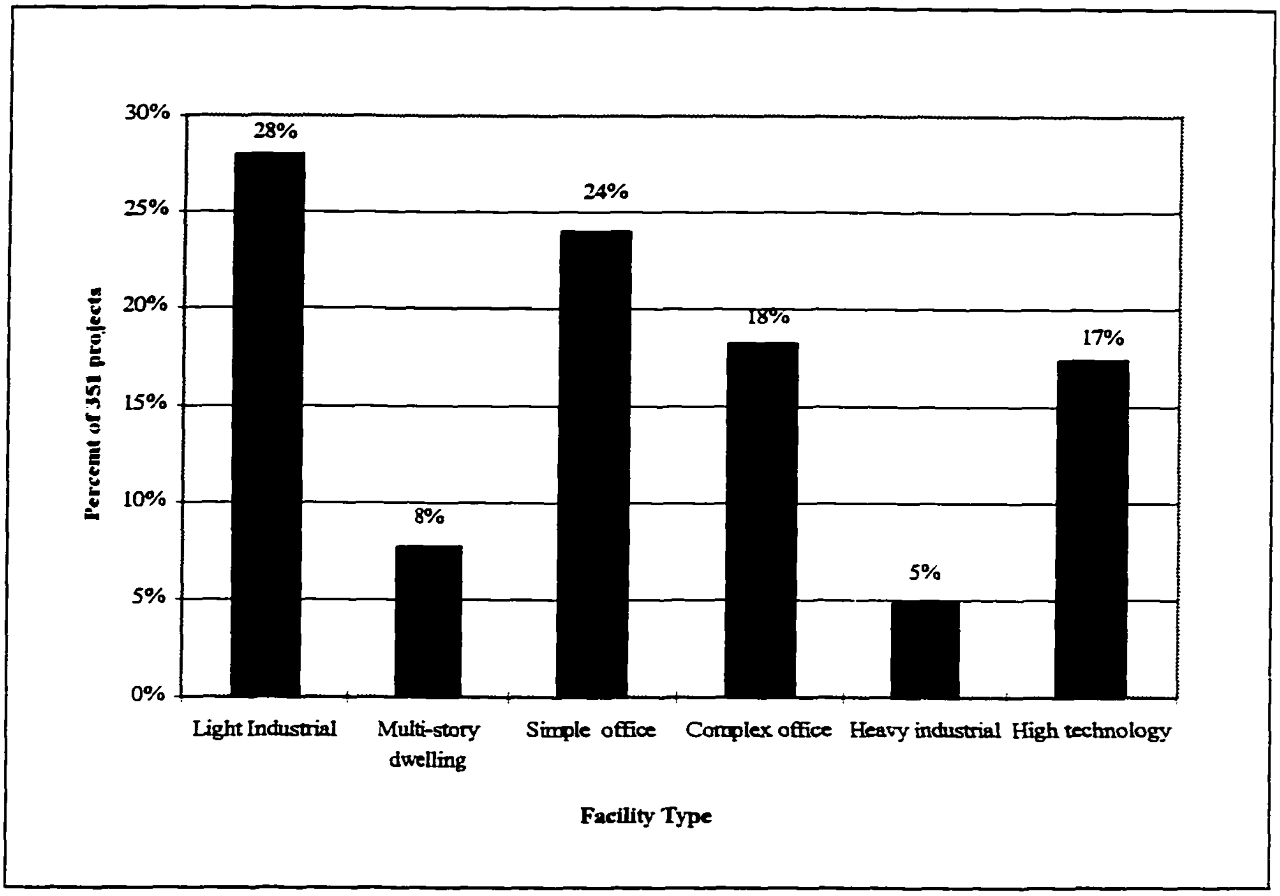

Figure 6.1: Distribution by facility type.

Projects were drawn from two client types, public and private. Public owners included local, state and federal agencies and the department of defense. Public projects such as schools, courthouses, prisons, military base commissaries and dormitories, and hospitals were included. Fifty seven percent of the 351 projects surveyed were privately owned and 43% were owned publicly.

Projects ranged in size from 5000 square feet to over two million square feet. Figure 6.2 charts seven intervals of project size. Each interval represents 100,000 square feet except the first and last interval. Just over a quarter of the projects were less than 50,000 square feet in size and one third of all projects fell in the range of 50,000 to 150,000 square feet. Several large projects were also included in this sample. Of the 24 projects larger than 550,000 square feet, 9 were greater than one million square feet.

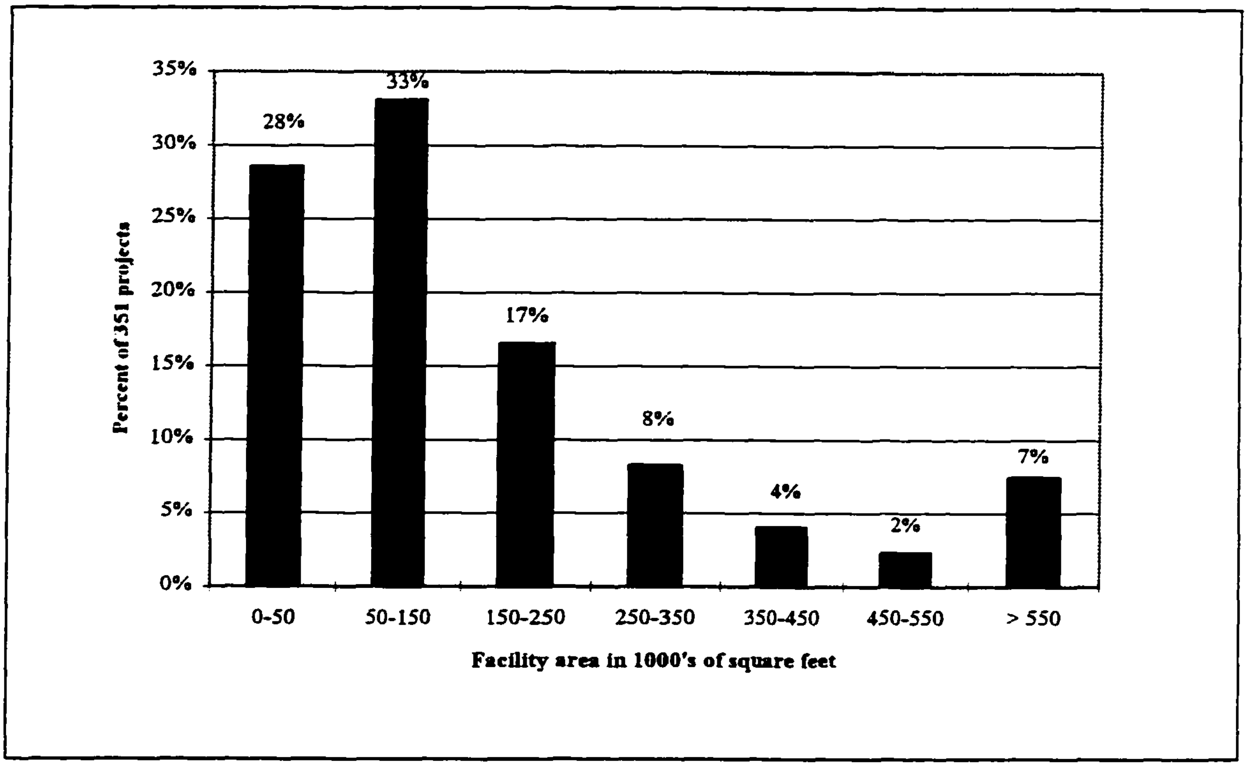

Figure 6.2: Distribution of project size in square feet.

Figure 6.3 shows that over a quarter of all projects had unit costs between 60 and 100 dollars per square feet. Nineteen percent of projects were seen in the intervals on either side of this largest group. In addition, 19% of all projects had unit costs greater than 180 dollars per square foot. It is interesting to note that high technology projects had median and mean unit costs of 189 and 295 dollars per square foot respectively. When comparing this information to that illustrated in Figure 6.1, one can see that technology projects (17% of the entire sample) accounted for the majority of the very large categories of project unit cost. In a similar fashion, light industrial facilities typically had relatively low unit cost values, less than 60 dollars per square foot by median. Therefore, it is likely that the 21% of projects shown in Figure 6.3 that are less than 60 dollars per square foot, are represented within the light industrial facility class which makes up 28% of the entire project sample.

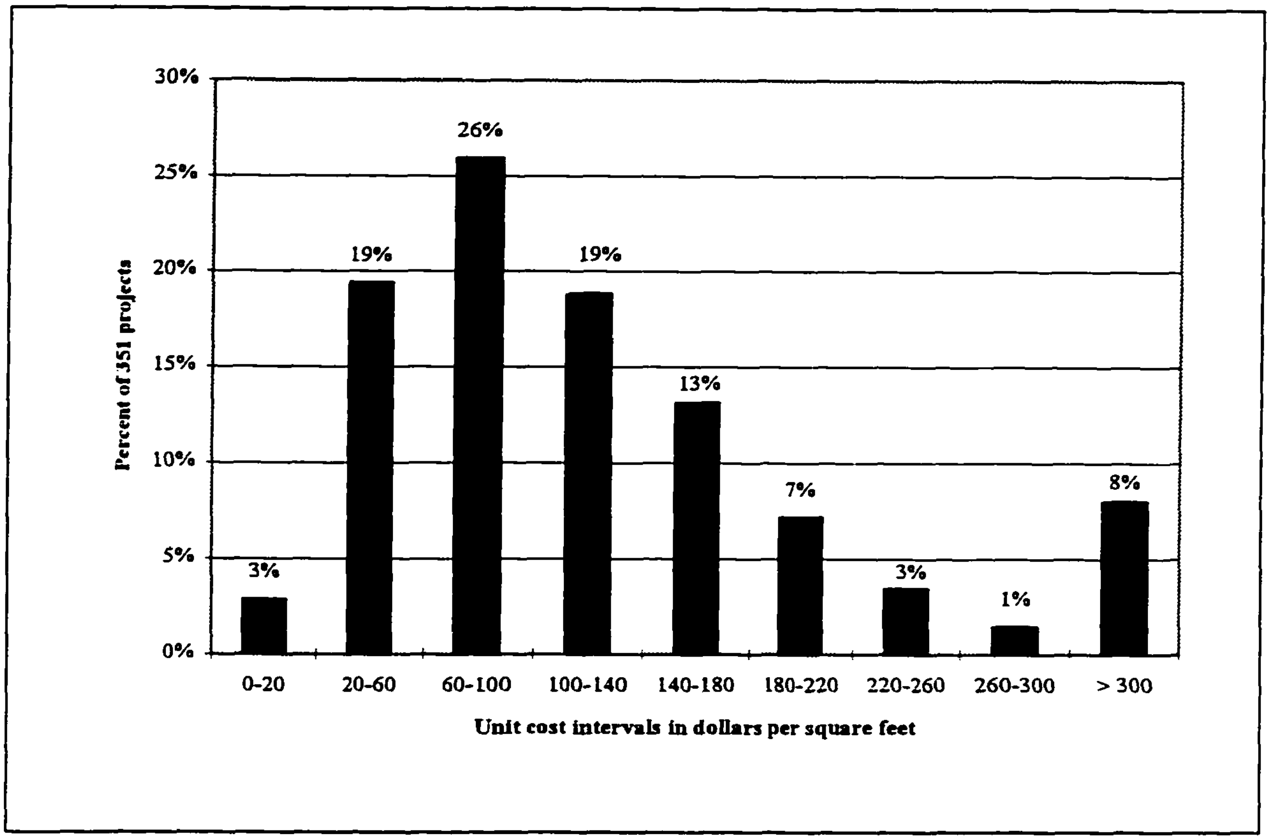

Figure 6.3: Distribution of project unit cost in dollars per square feet.

Projects were submitted from a variety of industry sources. Companies that belong to organizations such as the CII, DBIA, AGC, PACE and several Penn State alumni all provided project data. Of the 351 projects submitted, 32% were received from private and public owners, 28% from design-build entities, 8% from architects and designers and 32% were submitted by general contracting or construction management firms. This relatively equal distribution, aside from the low submission by the architect group, indicated that a several company types were represented in this study.

6.2 UNIVARIATE RESULTS

This section describes results for one key performance indicator at a time. Appendix B presents summary data, sorted by delivery system, for all 351 projects. This section describes the salient features of the data.

Each sample mean and median was tested for comparison at a 95% confidence level, (p=0.05). Therefore, no significance is reported unless test values for both sample means and medians achieve this level of confidence (a p-value less than 0.05). From this point, p-values are reported for each relationship by a (0.05, 0.05) designation. The first p-value represents the sample mean test, the second represents the sample median test.

6.2.1 UNIVARIATE COST RESULTS

Figure 6.4 illustrates the difference between delivery system using median unit costs. Design-build (0.055, 0.002) projects had a median unit cost nearly a third less than design-bid-build projects. This comparison was extremely close to being significant. Design-build (0.18, 0.002) was not significantly less than construction management at risk unit cost. The maximum standard error for all unit costs was plus or minus 18.3 dollars per square foot. This represents one half of the range for the largest 95% confidence interval calculated for any of the delivery systems for unit cost.

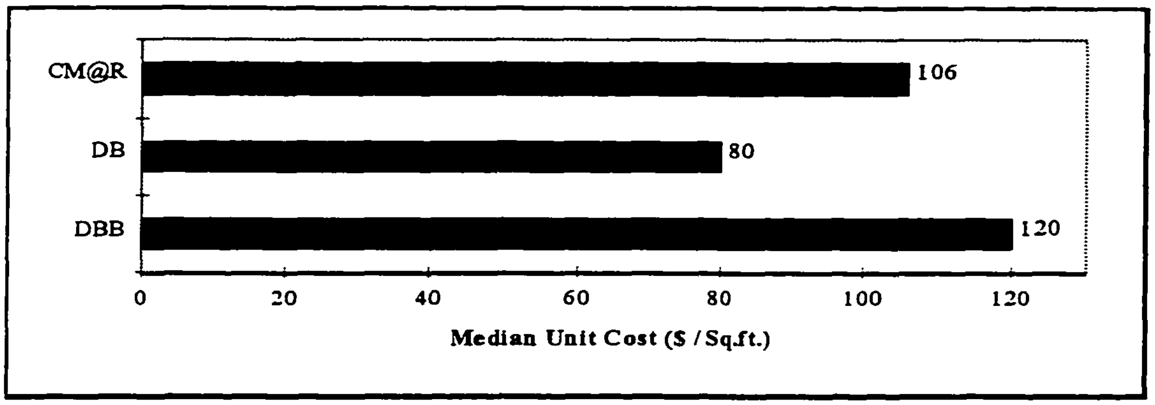

Figure 6.4: Median unit cost by delivery system.

Figure 6.5 indicates a similar situation for project cost growth. Here design-build projects, had less cost growth than either construction management at risk or design-bid-build. However, results indicated that both construction management at risk (0.029, 0.008) and design-build (0.007, 0.008) significantly outperformed design-bid-build in terms of sample cost growth. The maximum standard error for cost growth was plus or minus 2.2%.

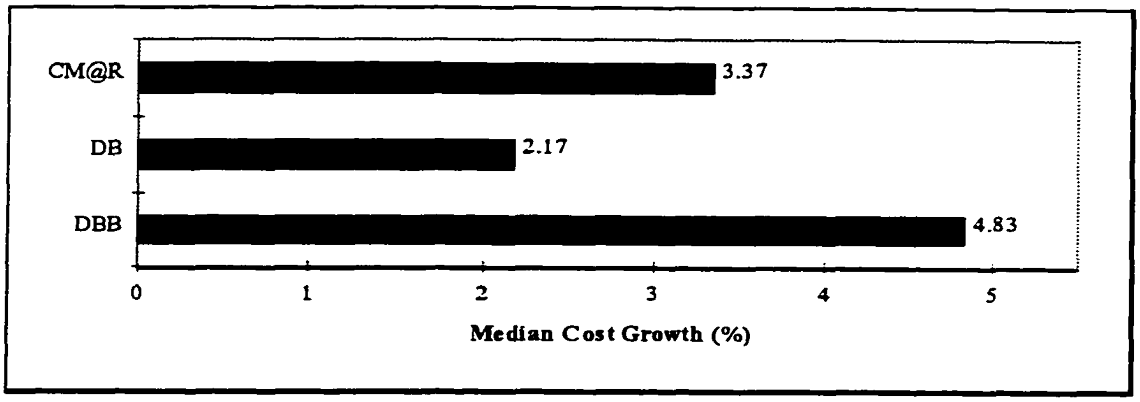

Figure 6.5: Median cost growth by delivery system.

The distribution or range of cost growth performance by system is explored in Figure 6.6. The center horizontal line in each boxplot represents the median values for cost growth. Fifty percent of each sample falls within the bounds of each respective box.

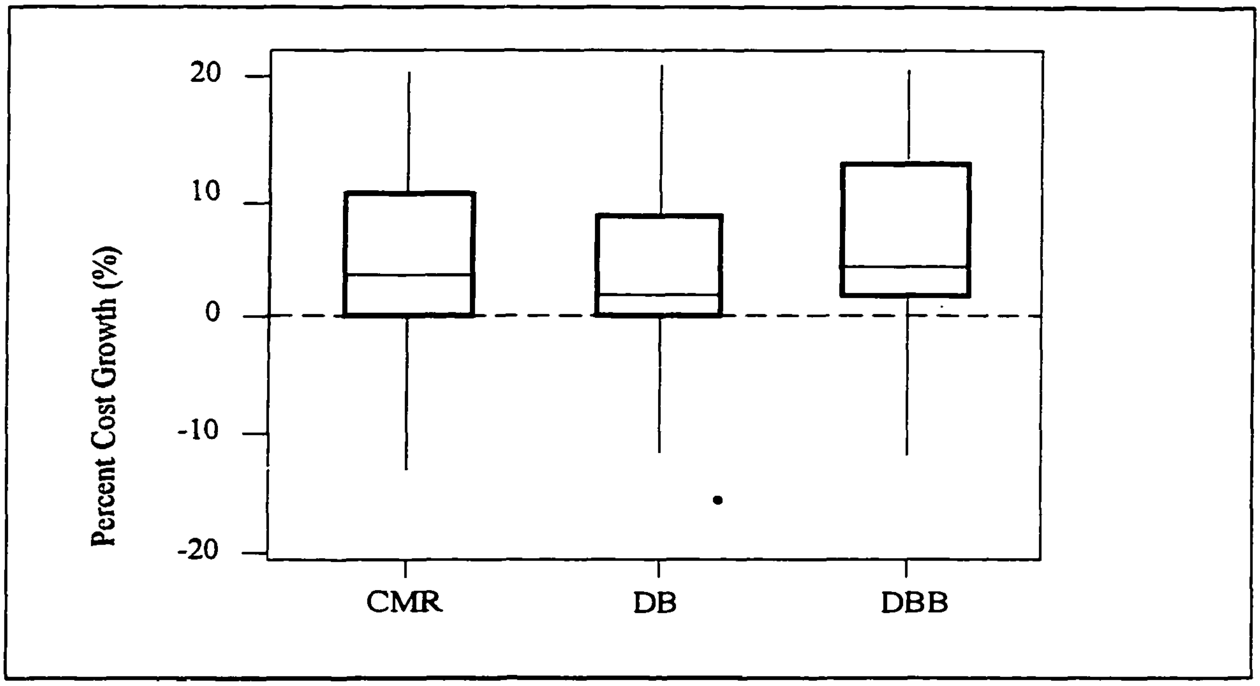

Figure 6.6: Cost growth distribution by delivery system.

The bottom and top of the each box indicates the upper and lower quartiles of each sample. This reports that 25% of all design-bid-build and construction management at risk projects experience cost growth over 10%. Conversely, 25% of design-build and construction management at risk projects fall at or below zero cost growth, indicating that the likelihood for cost growth using these systems is slightly less than that using design-bid-build.

Figure 6.7 investigates the percentage of projects whose final costs exceeded the contract price by more than five percent, those that fell within plus or minus five percent of contract price and those that under ran contract price by more than five percent. Completion on contract amount indicates whether one delivery system consistently provided clients with greater cost certainty. Across the whole sample of projects, design-build projects were more likely to be completed within five percent of the contracted price than projects using either construction management at risk or design-bid-build. Design-build projects were also less likely to experience overruns exceeding the contract cost by more than five percent.

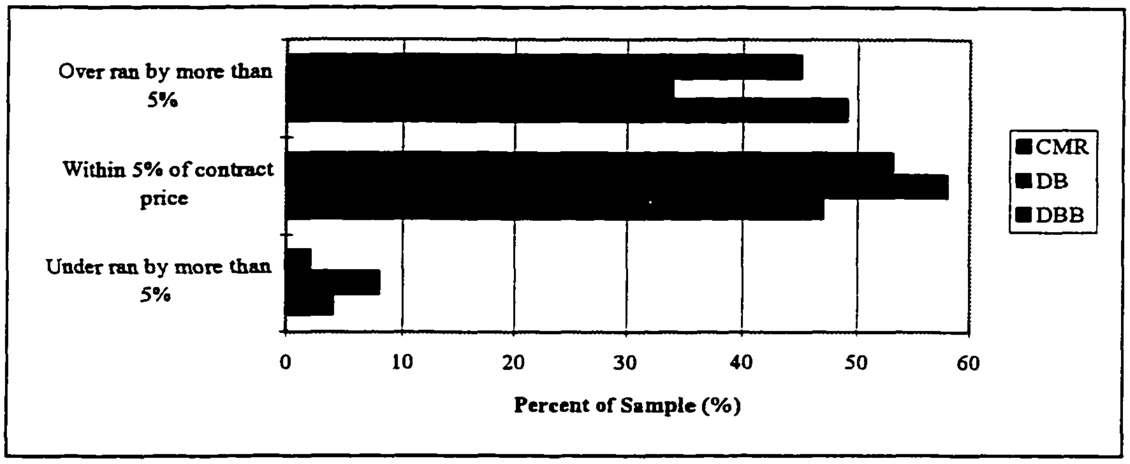

Figure 6.7: Certainty of completion on contract price.

6.2.2 UNIVARIATE SCHEDULE RESULTS

Figure 6.8 illustrates delivery system schedule performance in terms of percentage growth. Both design-build (0.03, 0.0) and construction management at risk (0.008, 0.0) significantly outperformed design-bid-build in terms of schedule growth. The maximum standard error for schedule growth was plus or minus 1.7%.

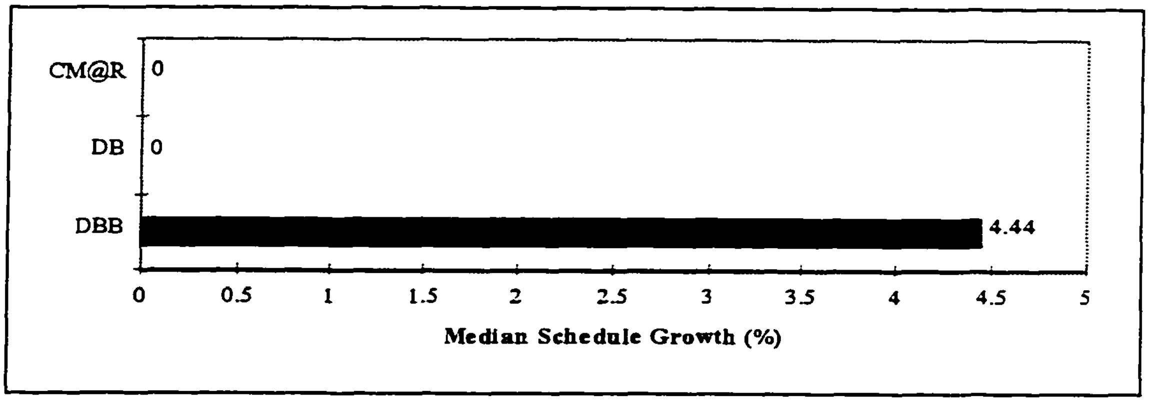

Figure 6.8: Median schedule growth by delivery system.

Figure 6.9 shows representative boxplots for schedule growth by delivery system. The distribution of each sample shows, in greater detail, the consistent schedule performance of construction management at risk and design-build. Fifty percent of all construction management at risk and design-build projects fell below zero percent schedule growth. This represents an area of significant difference over the performance of design-bid-build, where 50% of the projects were more than four percent late in completion.

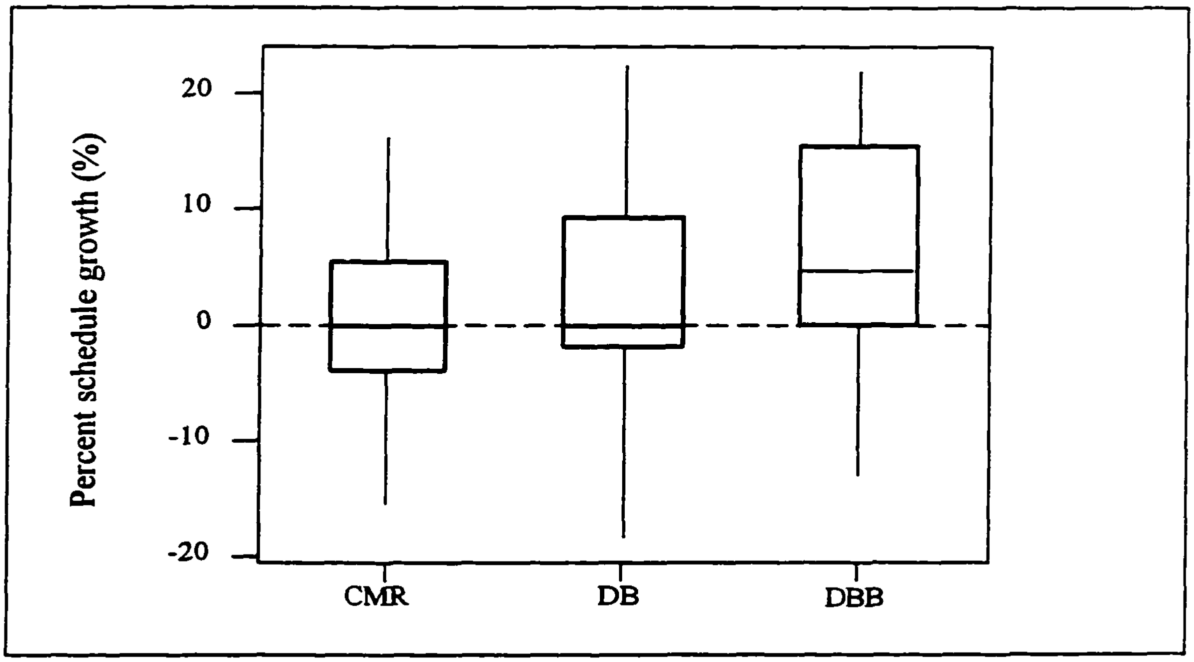

Figure 6.9: Schedule growth distribution by delivery system.

Figure 6.9 also illustrates that two of the three samples were highly skewed, or like other sorts of the same data set, depart from symmetry. Therefore, significance testing of sample means and medians assisted in making conclusions about the differences between system performance.

Figure 6.10 displays the percentage of projects whose final schedule duration exceeded the planned schedule by more than five percent, those that fell within 5% of the planned schedule duration and those that under ran the planned duration by more than five percent. In contrast to the cost growth results, construction management at risk had more certainty of completion on time whereas nearly half of all design-bid-build jobs were more than 5% late. Less than ten percent of all design-bid-build projects experienced significant schedule savings. Design-build projects did tend to perform more consistently than other delivery systems. Almost half of all design-build projects finished on time and 19% of them finished earlier than scheduled durations.

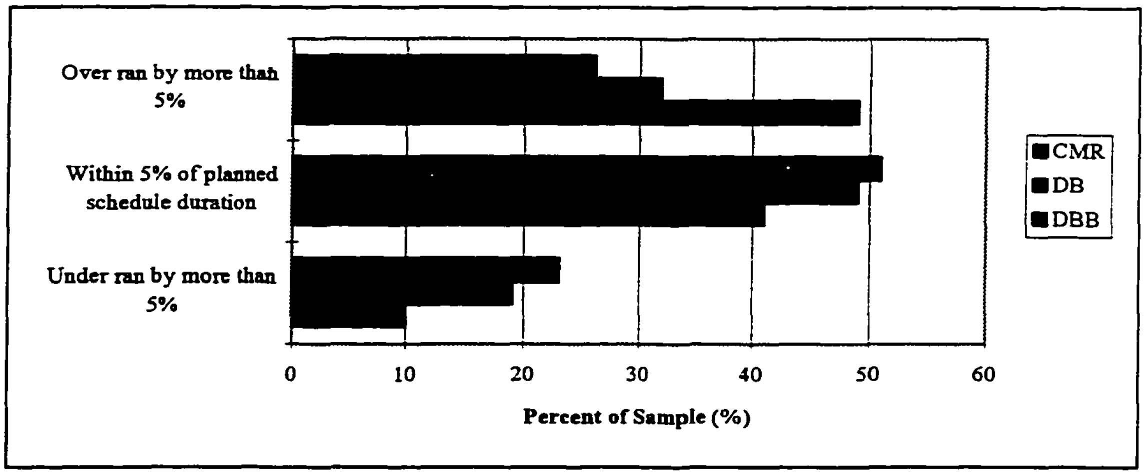

Figure 6.10: Certainty of completion on time.

Figures 6.11 and 6.12 report results for construction speed and delivery speed respectively. Construction speed was defined as the facility gross square footage divided by the as built construction time. Considering construction speed alone, design-build (0.007, 0.044) was significantly faster than design-bid-build. Design-build (0.09, 0.044) was also very close to significantly outperforming construction management at risk as well, but the margin between these systems was much less. Construction management at risk (0.054, 0.044) was also close to significantly outperforming design-bid-build. The maximum standard error for construction speed was plus or minus 2,372 square feet per month.

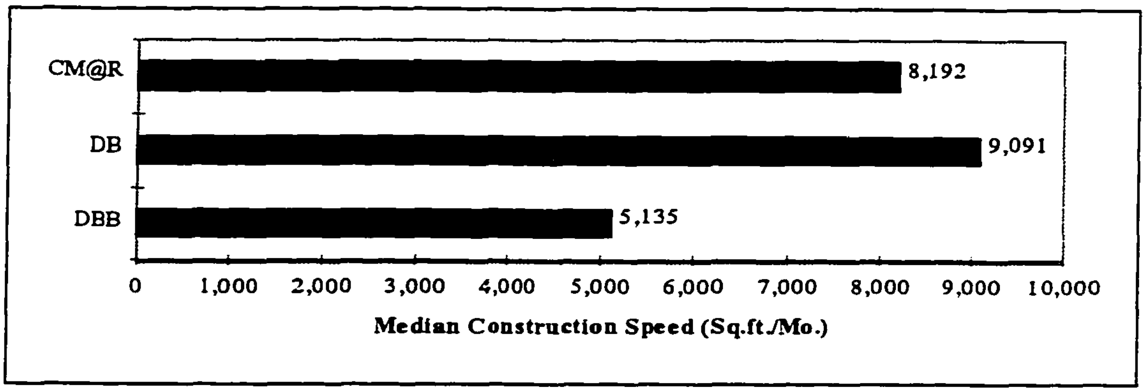

Figure 6.11: Median construction speed by delivery system.

Delivery speed was defined as the facility gross square footage divided by the design and construction as built time. Using the delivery speed metric, margins between systems became much greater. In fact, design-build (0.03, 0.002) had significantly greater delivery speeds than construction management at risk and design-bid-build (0.00, 0.002). In addition, construction management at risk (0.039, 0.002) significantly outperformed design-bid-build. It was expected that the lack of an additional bidding cycle and the overlapping of design and construction, generally required for the procurement of construction contractors, increased delivery speed values of design-build projects. The maximum standard error for delivery speed was plus or minus 2,050 square feet per month.

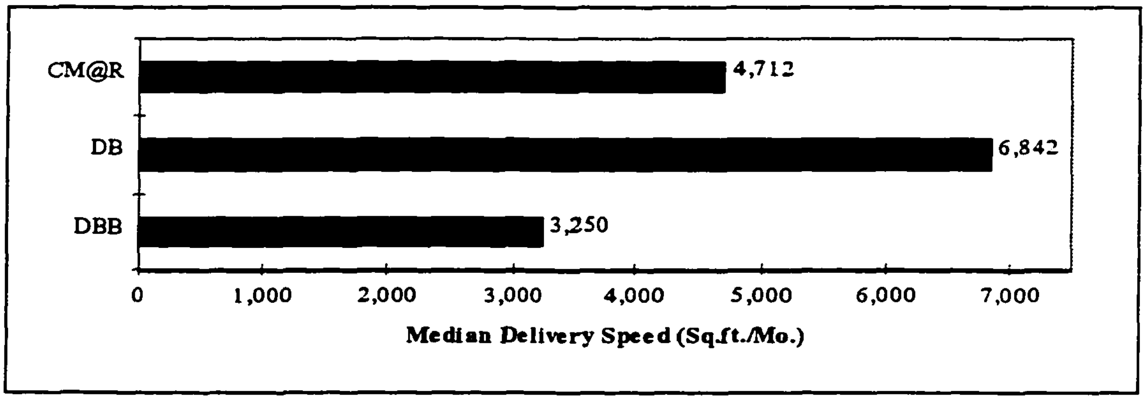

Figure 6.12: Median delivery speed by delivery system.

Figure 6.13 shows project intensity. Intensity measured the unit cost of design and construction work put in place in a facility per unit time. Intensity accounts for the higher level of activities required for certain complex facilities than in simpler facilities with the same building area (Riley, 1994).

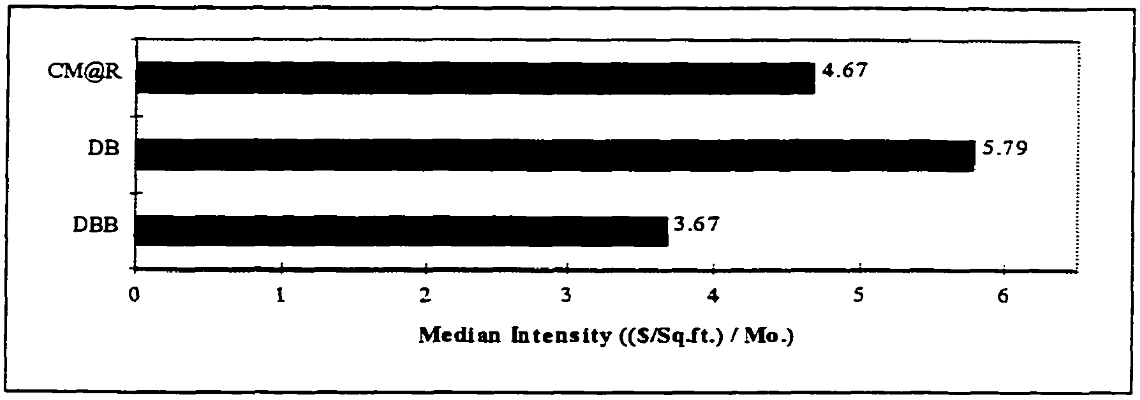

Figure 6.13: Median intensity by delivery system.

No system significantly outperformed the others. The maximum standard error for intensity was plus or minus 1.2 (($/Sq.ft.)/Mo.).

6.2.3 UNIVARIATE QUALITY RESULTS

Quality performance was measured in seven specific areas. Mean scores are reported because they better represent the central tendency of a discrete variable whose scale is fixed. Therefore, only sample mean tests (p-values) are reported. A score of 10 on the horizontal axis indicates the highest level of achieved quality. Quality was recorded separately for the turnover process and for the performance of specific systems. This was done to eliminate any owner bias present from a highly difficult turnover process. A poor turnover process may lead to a poor quality perception for the facility and bias the scoring of individual system quality. The maximum standard error for all quality metrics was plus or minus 0.19.

Figure 6.14 indicates mean scores for the quality of the turnover process by delivery system. In the turnover process, a score of 10 represents low difficulty of facility startup, a low number of call backs or low operation and maintenance costs for the facility. A score of five represents there was medium difficulty and a score of zero reveals high difficulty, the worst possible outcome. Design-build (0.0003) and construction management at risk (0.003) significantly outperformed design-bid-build in start up quality. Design-build (0.01) and construction management at risk (0.007) significantly outperformed design-bid-build in terms of callbacks. Design-build significantly outperformed both design-bid-build (0.024) and construction management at risk (0.017) in terms of operation and maintenance quality.

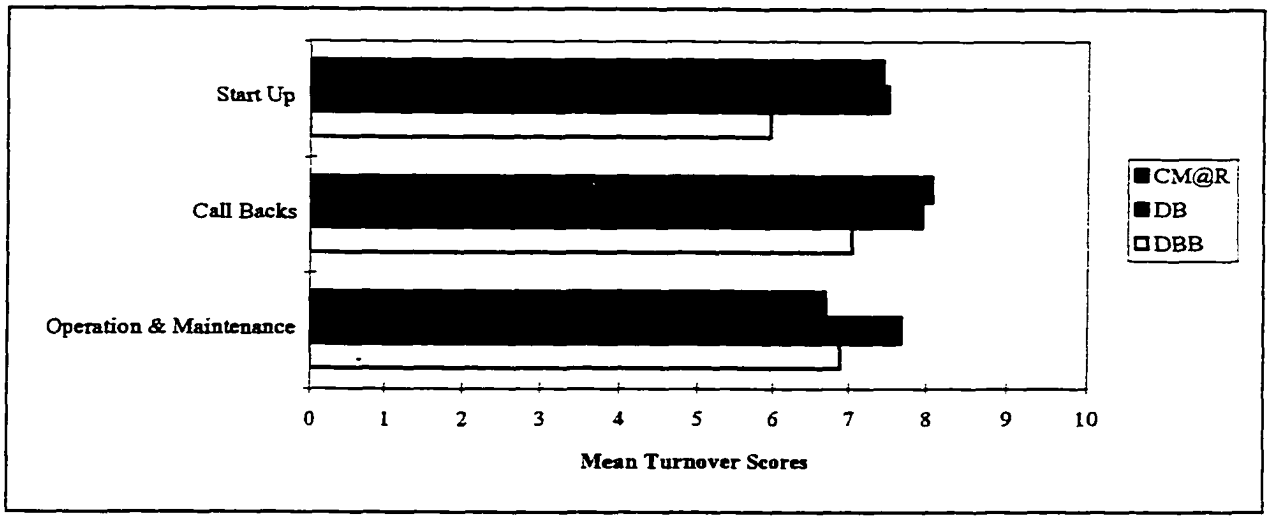

Figure 6.14: Turnover process quality.

Figure 6.15 presents system performance quality. A high score of 10, indicates that the listed system had exceeded the quality expectations of the client. A score of five shows that the owner's expectations were being met whereas a system scoring zero was not meeting the expectations of the client. In Figure 6.15 it is interesting to note that design-bid-build projects, on average, barely met owner expectations in terms of system performance. Design-build (0.008) significantly outperformed design-bid-build in terms of the envelope, roof, structure and foundation (ERSF) systems but did not outperform construction management at risk. Construction management at risk (0.09) was almost significant when compared to design-bid-build in this category. Design-build (0.0008) and construction management at risk (0.002) both significantly outperformed design-bid-build in the interior space and layout quality category. None of the three systems experienced superior environmental system performance. However, construction management at risk (0.079) was almost significant when compared to design-bid-build. Where process equipment and layout was described, design-build (0.04) significantly outperformed design-bid-build where construction management at risk (0.08) was barely insignificant over design-bid-build.

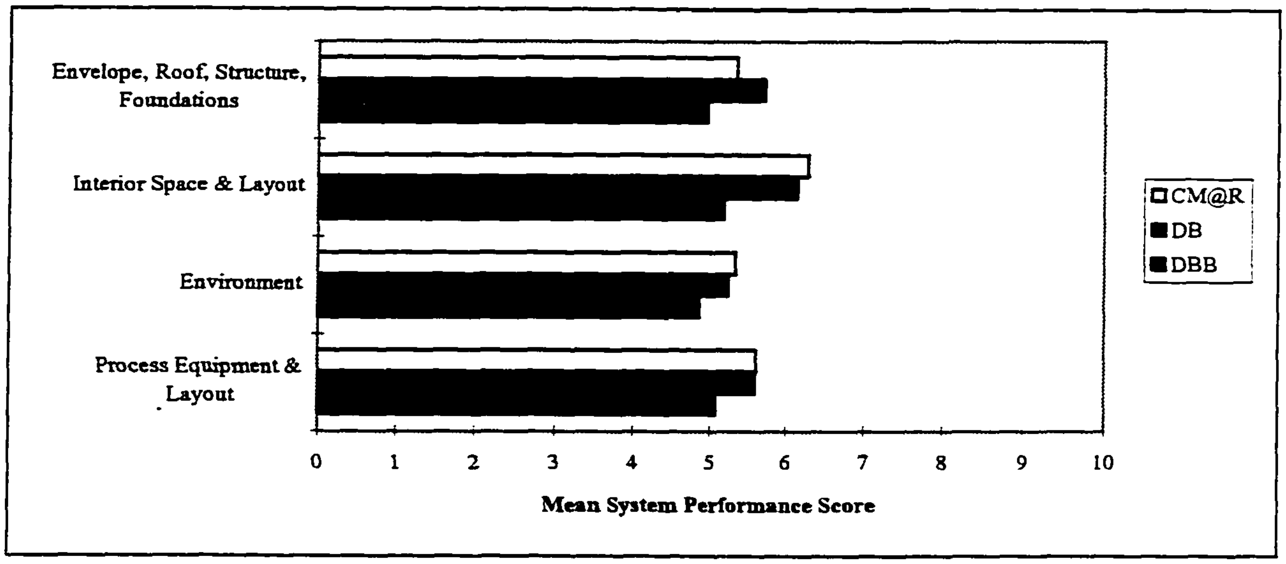

Figure 6.15: System performance quality.

It is clear from these results that design-build projects achieved equal if not better quality results than other projects studied. In particular, design-build offered significantly better quality results than design-bid-build in all categories except that of interior space and layout. Design-build significantly outperformed construction management at risk in only one area, operation and maintenance cost.

In this thesis, quality results are offered on a univariate basis only. Quality is the least objective of all the performance metrics that were calculated. This is because the quality questions were asked of clients after project completion, where any number of factors could have affected the perception of quality performance. Significant quality differences did exist however, and quality results have the same degree of statistical confidence (95%) as do other principal metrics. Each classification of facility type, owner type and delivery system alone explore quality on a univariate basis.

6.3 UNIVARIATE RESULTS BY FACILITY TYPE

Comparisons of delivery systems for each metric were made in the previous section regardless of facility type. However, each facility type represents an important subset of the entire sample of 351 projects. Figure 6.16 illustrates the result of testing for significance within each facility class by delivery system. Tabulated data, sorted by facility type and by delivery system for all projects can be found in Appendix B.

Cells with solid circles indicate significant differences between systems. Certain comparisons, such as in the case of unit cost of light industrial facilities, show that projects using design-build and construction management at risk significantly outperformed those using design-bid-build. However, the same cannot be said for the difference between design-build and construction management at risk. Of the 17 areas where significant differences were found, in no case did design-bid-build outperform either of the other two delivery systems. In general, design-build projects resulted in the best project performance in facilities with the highest degree of complexity such as complex office buildings, high technology facilities and light industrial facilities. In general, construction management at risk delivery system resulted in project performance superior to that of design-bid-build when used on facility types such as simple office buildings and light industrial projects.

Quality is illustrated using the summary metrics of turnover quality, system quality and equipment quality. Aggregate scores were calculated by summing the scores of individual metrics within each group as defined in Chapter Three. Equipment quality was unique to only certain facility types such as light industrial and high technology projects and would therefore be misrepresented by grouping it with other common measures.

Metric Facility Type	Unit Cost	Cost Growth	Schedule Growth	Construction Speed	Delivery Speed	Intensity	Turnover Quality	System Quality	Equipment Quality
Light industrial	DB, CMR < DBB ●	○	CMR < DB, DBB ●	DB, CMR > DBB ●	DB, CMR > DBB ●	○	○	DB > DBB ●	○
Multi-story dwelling	○	○	○	○	○	DB > DBB ●	○	○	○
Simple office	○	○	CMR < DBB ●	○	CMR > DBB ●	DB > CMR, DBB ●	CMR > DB, DBB ●	○	○
Complex office	○	○	DB < DBB ●	○	○	DB > DBB ●	DB > CMR, DBB ●	○	DB > CMR ●
Heavy manufacturing	○	○	○	○	○	○	○	○	○
High technology	○	DB < DBB ●	○	○	○	DB > CMR ●	DB, CMR > DBB ●	DB > DBB ●	○

Legend

Significant differences called out	< or >
No significant differences between systems	○
Significant differences	●

Figure 6.16: Matrix of significance by facility type unadjusted for other explanatory variables.

6.4 UNIVARIATE RESULTS BY OWNER TYPE

Figure 6.17 illustrates delivery system performance adjusted for owner type, whether publicly owned or private. Design-build projects in the private sector performed significantly better than design-bid-build in six out of the nine performance categories. Again, in no instance did design-bid-build project delivery outperform either construction management at risk or design-build delivery systems in public or private sectors. Performance within the public sector was similar. Design-build delivery again outperformed design-bid-build delivery in all measures of schedule performance, turnover quality and system quality. Construction management at risk produced significantly better results for schedule growth and turnover quality than did design-bid-build. The differences between design-build and construction management at risk were slight in the public sector whereas design-build outperformed construction management at risk in measures of schedule growth, delivery speed and lower unit costs in the private sector.

6.5 SUMMARY OF UNIVARIATE RESULTS

Over 300 interviews were conducted with clients and project team members who submitted project data. Interviews identified underlying causes of differences in project performance. Because of these interviews, the broad distribution of project respondent origin, and a large sample size, the researcher places a significant degree of confidence in the validity of project data and subsequent research results. This section has shown results and identified where significant differences exist between delivery systems. Univariate results were unadjusted for the variety of other variables that might affect project performance.

The univariate analysis was performed first to describe the impact that the information categories, outlined in the project delivery framework, had on facility delivery performance. Owner type and facility type were tested. These tests indicated strongly the presence of explanatory variables other than project delivery system. Thus direct, multivariate comparisons between project delivery systems were explored. These are presented and discussed in the following sections.

Metric / Owner Type	Unit Cost	Cost Growth	Schedule Growth	Construction Speed	Delivery Speed	Intensity	Turnover Quality	System Quality	Equipment Quality
Public Owner	○	○	CMR, DB < DBB ●	DB > DBB ●	DB > DBB ●	○	DB, CMR >DBB ●	CMR > DBB ●	○
Private Owner	DB < CMR ●	DB < DBB ●	CMR, DB < DBB ●	DB > DBB ●	DB > CMR, DBB ●	○	DB > DBB ●	DB > DBB ●	○

Legend

Significant differences called out	< or >
No significant differences between systems	○
Significant differences	●

Figure 6.17: Matrix of significance by owner type unadjusted for other explanatory variables.

6.6 PRIMARY MULTIVARIATE RESULTS

Multivariate analysis was performed to investigate whether significant differences discussed in previous sections were valid when other explanatory variables were considered. This analysis identified several areas where the presence of other variables, besides those of facility and owner type, significantly affected project performance. Therefore, the multivariate approach offered a more complete explanation of project delivery variations. In addition it allowed the researcher to investigate other areas of the project delivery framework presented in Chapter Three.

The following sections discuss conclusively the measured differences between construction management at risk, design-build and design-bid-build when adjusted for all variables measured. Regression models for unit cost, construction speed and delivery speed are presented as primary results. These three models explained the highest level of variation about unit cost and speed. Therefore a high level of certainty is placed in these conclusions. Each model first presents summary statistical results before it identifies the level of explained variation and number of projects used to build the model. Finally, variables that accounted for the greatest proportion of explained variation were rank ordered.

6.6.1 UNIT COST

Multivariate regression analysis was used to develop a model to explain the variability of unit cost among all projects. Cost per square foot was defined as the final design and construction cost, divided by building gross square footage. Unit cost was also adjusted for time and location using historical cost indices. Using regression, the effects of each delivery system on unit cost were separated from the effects of other explanatory variables. This process allowed the researcher to investigate a number of variables in a single model.

When all other variables were held constant, the effects of delivery system indicated the unit cost of design-build projects to be at least 6.1% less than design-bid-build and 4.5% less than construction management at risk projects. In addition, the unit cost of projects using construction management at risk was 1.6% less than design-bid-build.

Complete regression analysis for the unit cost model, the model, supporting residual diagnostics and a discussion of specific procedures used to build this model can be found in Appendix C.

Using data from 316 projects, the model identified key explanatory variables that together explained 99% of the variation in unit cost. The number of projects used to build the model was slightly less than the total sample size because only projects where all the required data was available from the survey were included. For example, a full service, design-build firm would not rate the experience of the contractor, instead they would rate the experience of the design-builder. Therefore, if the experience of the contractor was a critical variable in the model, then this data would be unavailable in certain cases. In addition, the performance or characteristics of certain jobs when included in the model were causing high levels of actual influence in the model. This was examined more completely using Cook's influence (Neter, 1996). As a result, four specific jobs were removed from the model. These jobs were extreme outliers, and forced the model to inaccurately adjust for their presence. Two jobs were from the light industrial class, one was a heavy industrial facility and another was a multi-story dwelling. Each job had unusually high unit cost values. In particular, the fourth project was a large public prison renovation with a poorly defined scope.

The model for unit cost explained 99% of the variation and used a very large number of projects, thus, it provided a great deal of statistical confidence. The four variables which accounted for the greatest proportion of variation, in order of importance, were:

1. Contract unit cost,
2. Facility type,
3. Project size, and
4. Delivery system.

Perhaps the most telling variable was the *contract unit cost* calculated at the time of contract award. This value was calculated using contract design and construction cost divided by gross square footage. Knowing this value prior to the start of the project greatly increased the performance of the model. In fact it explained the largest proportion of the variation in this model. The direct relationship of this variable to actual unit cost was not linear. A log transformation between both variables was used. The relationship indicated that contract unit cost was positively related to the final unit cost. For instance, as the contract unit cost increased, final unit cost also increased, but in a log fashion.

A review of the other variables indicated their presence in the model to be logical. For example, light industrial projects, on average, were lower in unit cost than high complexity projects. Therefore the *facility type* acting alone or in combination with other explanatory variables affected the outcome of unit cost. For instance, each facility type had a negative relationship to unit cost when compared to the high technology facility class. In other words, in the presence of certain facility classes besides high technology, unit cost decreased. One exception was noticed in the heavy industrial class. This class increased unit cost. *Project size* contributed significantly to the explanation of unit cost. However, the direct relationship between unit cost and project size in this model was not linear. These variables were better related by using a log transformation that allowed the model to better fit project data. It was quite clear that unit cost increased dramatically in a log fashion with decreased values of project size. Regression analysis, through the use of transformations, allowed the model to accommodate relationships of this nature. Furthermore, project size was interacting with certain facility types. One interacting variable between facility type six and project size was included in this model. This variable indicated that the effect of facility type six depends largely on the size of the project. Finally, the model also demonstrated that the choice of *delivery system* was an important explanatory variable for cost.

Regression also tracked the impact that projects from different samples had on model performance. Whether or not a project was submitted from the industry during the original sampling or as part of the non-response study had no significant bearing on the model for unit cost.

6.6.2 CONSTRUCTION SPEED

Multivariate regression analysis was also used to develop a model that explained the variability of construction speed among all projects. Construction speed was defined as the building gross square footage divided by the as built construction duration. Using regression, the effects of each delivery system on construction speed were separated from the effects of other explanatory variables. This process allowed the researcher to investigate a number of variables in a single model.

When all other variables were held constant, the effects of delivery system indicated that design-build was at least 12% faster than design-bid-build and 7% faster than construction management at risk in terms of construction speed. In addition, construction management at risk was at least 5.8% faster than design-bid-build. Complete regression analysis data for the construction speed model, the model, supporting residual diagnostics and a discussion of specific procedures used to build this model can be found in Appendix C.

Using data from 344 projects, the model identified six key explanatory variables that together explained 89% of the variation in construction speed. As was the case in the unit cost model, the performance and characteristics of certain jobs were causing high levels of actual influence in the model. This was again examined more completely using Cook's influence. As a result, two specific jobs were removed from the model. One was a complex office renovation project with many legal constraints, the other a high technology renovation project where 50% of the design was complete prior to the construction manager joining the team. These jobs were extreme outliers, and forced the model to inaccurately adjust for their presence.

The model for construction speed explains a high level of variation (89%) and uses a very large number of projects (344), thus, it provides a great deal of statistical confidence. The six variables that accounted for the greatest proportion of variation, in order of importance, were:

1. Project size,
2. Contract unit cost,
3. Delivery system,
4. Percent design complete before construction entity joined the project team,
5. Project team communication, and
6. Project complexity.

Construction speeds were significantly faster on projects with larger areas. Construction speed and *project size* were highly correlated, evident from a correlation coefficient of 0.74. Perhaps equally important as the strength of correlation is that the relationship is positive. Again, within the construction speed model, the relationship between construction speed and area was best represented linearly through a log transformation.

Construction speed held a negative relationship with *contract unit cost*. Although the strength of correlation was lower than with project size, -0.24, the direction is important. Here, construction speed decreases with increasing values of unit cost. Likewise, construction speed decreased with higher levels of project complexity, although only slightly.

The model also demonstrated that the choice of *delivery system* was an important explanatory variable for construction speed. Here, speed levels increase when construction management at risk or design-build was used. There was an interacting effect between design-bid-build and the size of the facility. This interaction indicated that design-bid-build construction speeds decreased slightly with increasing project sizes.

Design advancement represents the *percent of design complete* when the construction entity joined the project team. A negative relationship existed between design advancement and construction speeds. Higher levels of construction speed were experienced the earlier the construction entity joined the project team. In addition, *team communication* had a positive relationship with construction speed. The presence of excellent communication amongst team members on a project had a significant impact on the level of construction speed achieved across all projects.

Project complexity negatively impacted construction speed performance. Facility types such as complex office and high technology buildings, when present, had lower levels of construction speed than did other facility types.

As in the unit cost model, contract unit cost accounted for a large portion of the variation in the construction speed model. Contract unit cost was calculated by dividing the contract amount by the gross square footage of the facility prior to the project start.

Whether or not a project was submitted from the industry during the original sampling or as part of the non-response study had no significant bearing on the model for construction speed.

6.6.3 DELIVERY SPEED

Multivariate regression analysis was also used to develop a model to explain the variability of delivery speed among all projects. Delivery speed was defined as the building gross square footage divided by the design and construction as built time. Using regression, the effects of each delivery system on delivery speed were separated from the effects of other explanatory variables. This process allowed the researcher to investigate a number of variables in a single model.

When all other variables were held constant, the effects of delivery system indicated design-build to be at least 33.5% faster than design-bid-build and 23.5% faster than construction management at risk in terms of delivery speed. In addition, construction management at risk was at least 13.3% faster than design-bid-build. Complete regression analysis data for the delivery speed model, the model, supporting residual diagnostics and a discussion of specific procedures used to build this model can be found in Appendix C.

Using data from 328 projects, the model identified ten key explanatory variables which together explained 88% of the variation in delivery speed. The number of projects used to build the model was slightly less than that in the construction speed model, primarily due to the increased number of indicator variables considered important to this model. As was the case in other models, the performance and characteristics of certain jobs when included in the model caused high levels of actual influence in the model. This was again examined more completely using Cook's influence. As a result, only one specific job was removed from the model. This project was a 3000 square foot, publicly owned simple office building with a project duration of over four years. Characteristic of some public jobs where funds are appropriated separately for design and construction services, this project design was completed two and a half years before construction bids were solicited. This was a direct cause of poor delivery speed performance.

The model for delivery speed explains a high level of variation (88%) and uses a large number of projects (328), thus, it provides a great deal of statistical confidence. The five variables which accounted for the greatest proportion of variation, in order of importance, were:

1. Project size,
2. Contract unit cost,
3. Percent design complete before construction entity joined the project team,
4. Facility type, and
5. Project team communication.

It is important to recognize the project delivery, although still significant, has become less important. It is now within a list of explanatory variables found to have a lesser impact on delivery speed performance. These include:

1. Excellent subcontractor experience with the facility,
2. Project complexity
3. Delivery system,
4. Level of new construction, and
5. Presence of onerous clauses in contracts.

A review of each of these variables indicates their presence in the model to be logical. Similar relationships were found between the top five variables as were discussed for construction speed. An exception is made for *contract unit costs*. As unit costs and project complexity increased, delivery speed decreased. This is logical considering the coordination required between design and construction teams on either highly complex or high unit cost projects. *Delivery system* and *project complexity* had a lesser effect on variation in total delivery speed. Although they remain significant indicators, both drop from the top five explanatory variables. Relationships using log transformations for speed, unit costs and project size were required to build the multivariate linear model.

Delivery speeds were significantly higher on design-build projects, where the need to bid construction work separately from design services is eliminated. In addition to delivery speed, the *level of new construction* was also important in this model. Projects with a proportion of new construction greater than 95% achieved significantly higher delivery speeds than renovation (less than 20%) projects. However, because of the large number and variety of projects that had greater than 95% new construction, delivery speeds varied substantially. This fact was reflected by the very small, negative coefficient calculated within the regression model. Therefore, it was useful to know if a project was new or renovated, but the change in delivery speed performance was minimal.

Facility type was again critical in explaining delivery speed variation. However, only particular facility types were considered significant. Light industrial and heavy industrial facilities were both positively related to delivery speed. The model clearly indicated that these facility types produce greater levels of delivery speed. This fact was substantiated by the univariate analysis for delivery speed by facility type. Light and heavy industrial facility types both had significantly higher levels of delivery speed than did other facility classes.

Also, *team experience* surfaced as an important explanatory factor for delivery speed. Of particular importance, excellent facility experience by subcontractors positively affected delivery speed performance. Opposite from good team experience, the presence of *onerous clauses* with contracts caused delivery speeds to suffer. In other words, when onerous contract clauses were numerous, delivery speed decreased.

Whether or not a project was submitted from the industry during the original sampling or as part of the non-response study had no significant bearing on the model for delivery speed.

6.7 SECONDARY MULTIVARIATE RESULTS

The following sections discuss the measured differences between construction management at risk, design-build and design-bid-build adjusted for all collected variables. Regression models for cost growth and schedule growth are presented here as secondary results because the variables explain a very low percent of the model's variation. Models for cost and schedule growth achieve explained variation in the low twenty percent levels. This is due in large part to the nature of these metrics where a result of zero or negative percent growth for both cost and schedule is most desirable. This is a good reason why these model types have never been reported in the industry.

Each model is presented first with summary results, the level of explained variation and the number of projects used to build the model. Finally, variables that accounted for the greatest proportion of explained variation are rank ordered for each metric. Because of its hybrid development from cost and schedule measures like unit cost and speed, a detailed model for intensity was not developed. However, a simple analysis was performed to explore this model, and as expected, variables explaining its variation were nearly identical to those included within unit cost and speed models.

6.7.1 COST GROWTH

Multivariate regression analysis was used to develop a model to explain the variability of cost growth among all projects. Cost growth was defined as the percentage difference between contract and final cost of both design and construction costs. Using regression, the effects of each delivery system on cost growth were separated from the effects of other explanatory variables. This process allowed the researcher to investigate a number of variables in this model.

When all other variables were held constant, the effects of delivery system indicated design-build to be at least 5.2% less than design-bid-build and 12.6% less than construction management at risk in terms of cost growth. In addition, design-bid-build was at least 7.8% less than construction management at risk. Complete regression analysis data for the cost growth model, the model, supporting residual diagnostics and a discussion of specific procedures used to build this model can be found in Appendix C.

Using data from 196 projects, the model identified ten key explanatory variables which together explained 24% of the variation in cost growth. The number of projects used to build the model was significantly low. Due to the variety of variables used and the nature of these variables, over half of the projects had unavailable data. This and the relatively low level of explained variation led to high uncertainty for the cost growth model. The differences recognized between each delivery are valid. However, the explanation of these differences by specific explanatory variables was unclear. This model represents the first of its kind and, although it explains less than a quarter of the variation in growth, it identifies factors that are likely to cause growth in cost.

As was the case in other models, the performance and characteristics of certain jobs when included in the model caused high levels of actual influence in the model. This was again examined more completely using Cook's influence. As a result, three specific jobs were removed from the model. Two of these were high technology projects. One was a costly renovation, the other was an unusual chemical plant with a unit cost of 674 dollars per square foot. The third constituted an open-air pedestrian walkway on top of a seven story parking deck. This project had a peculiar unit cost for its class and was aggressively scheduled due to specific owner characteristics.

The model for cost growth contained a similar, yet smaller, sample of the variables used within other models. They explained a low level of variation while the model utilized a very low number of projects, providing a greatly reduced level of statistical confidence. However, given the variation explained, five variables which were statistically significant and accounted for the greatest proportion of variation, in order of importance, were:

1. Commercial terms,
2. Presence of onerous clauses in contracts,
3. Level of new construction,
4. Project team chemistry, and
5. Foundation type.

It is important to recognize that project delivery has become less important. It is now within a list of explanatory variables found to have a lesser impact on cost growth performance. These include:

1. Delivery system,
2. Facility type
3. Project complexity,
4. Contract unit cost, and

5. Presence of legal constraints.

A review of each of these variables indicates their presence in the model, in certain cases, to be logical. *Commercial terms* indicate the type of contract held between the owner and principal team members. Three contract types were included in the model. First, and of significant value, guaranteed maximum price contracts for design positively impacted cost growth. Both guaranteed maximum price contracts and cost reimbursable agreements between the owner and construction entity or design-build entity led to decreased levels of cost growth. Once again, a high level of *onerous clauses* written in these contracts had a severely negative impact on cost growth.

New construction projects and those with *excellent team chemistry* created improved cost growth performance. When these variables were present, cost growth was significantly less. Finally, the type of foundation used was found to impact cost growth performance. In particular, deep *foundation* systems such as caissons or piles, when used, decreased cost growth.

Delivery system and *facility type* affected cost growth in different ways. First, design-build, when present as a variable, decreased the level of cost growth, while construction management at risk increased cost growth. While both of these relationships were insignificant acting alone, their presence in the model gives an accurate indication of their relationship to cost growth.

Light industrial and high technology facility classes were found to have a negative effect on cost growth. The model indicates that when these project types were present, cost growth values will increase nearly two percent. Highly *complex* projects experience levels of cost growth which are nearly three percent higher than average or low complexity projects.

Contract unit cost had a positive effect on final cost growth. In other words, as contract unit costs went up, cost growth diminished. This is one area of particular interest because the relationship is less logical than others. Based on the previous relationships between particular facility types and cost growth, it was expected that higher unit costs would equate to higher levels of cost growth. However, due to the significant difference between light industrial unit costs and high technology unit costs, it is feasible that a relationship was reported which might not exist. This fact is substantiated in part by the extremely low value of the coefficient calculated for contract unit cost in the model. It showed that although the relationship is negative, the actual change in cost growth was very slight.

The *presence of regulatory or legal constraints* on a project also affected cost growth performance. However the relationship was such that the highest level of constraints present led to decreased levels of cost growth. This is the least significant variable in explaining cost growth.

Whether or not a project was submitted from the industry during the original sampling or as part of the non-response study had no significant bearing on the model for cost growth.

6.7.2 SCHEDULE GROWTH

Multivariate regression analysis was used to develop a model to explain the variability of schedule growth among all projects. Schedule growth was defined as the percentage difference between as planned and actual design and construction durations. Using regression, the effects of each delivery system on schedule growth were separated from the effects of other explanatory variables. This process allowed the researcher to investigate a number of variables in this model.

When all other variables were held constant, the effects of delivery system indicate design-build to be at least 11.37% less than design-bid-build and 2.18% less than construction management at risk in terms of cost growth. In addition, construction management at risk was at least 9.19% less than design-bid-build. Complete regression analysis data for the schedule growth model, the model, supporting residual diagnostics and a discussion of specific procedures used to build this model can be found in Appendix C.

Using data from 215 projects, the model identified eight key explanatory variables that together explained 24% of the variation in schedule growth. The number of projects used to build the model was significantly low, due to the variety and nature of variables used within the model. This and the relatively low level of explained variation, result in high uncertainty in the schedule growth model. This model represents the first of its kind and although it explains less than a quarter of the variation in growth, it identifies important indicators for schedule growth performance.

As was the case in other models, the performance and characteristics of certain jobs when included in the model caused high levels of actual influence in the model. This was again examined more completely using Cook's influence. As a result, four specific jobs were removed from the model. Two of these were light industrial projects, each having extremely high unit cost and schedule growth values. Project three was a complex office facility which had multiple owners and inadequate funding which together led to untimely decisions, poor communication and severe delays. The fourth project, a multi-story dwelling, experienced growth in schedule of 116% percent. Although thought to be successful in terms of schedule by the project respondent, this particular project was nearly two years behind schedule.

The model for schedule growth contained a variety of those variables used within other models. Applied here, they explain a low level of variation and utilize a reduced sample of projects, thus, the model provides limited statistical confidence. Four variables which were statistically significant and accounted for the greatest proportion of the variation, in order of importance, were:

1. Delivery system,
2. Excellent subcontractor experience with the facility,
3. Facility type, and
4. As planned schedule duration.

Project delivery system and *subcontractor experience* with the facility were the leading variables in the model for schedule growth. In fact, the variables of design-build and construction management at risk held the most significance in the determination of schedule growth. Both were positively related to schedule growth, whereas design-bid-build, when present, resulted in significantly higher levels of schedule growth. This fact was confirmed by the univariate analysis where both mean and median measures for construction management at risk and design-build were significantly lower than design-bid-build. *Facility type* also had a dramatic effect on schedule growth performance. Projects in the multi-story class had a very strong negative relation with schedule growth and over ran planned schedules more than any other facility type. Additionally, an interaction was present between facility class four and design-bid-build delivery. This interaction was quite significant and also had a negative impact on schedule growth when present. In other words, when complex office projects were delivered using design-bid-build they could expect significant schedule overruns.

As planned schedule duration offered a significant amount of explanation to schedule growth. As planned duration included the period from as planned start of design to the as planned substantial completion of construction. The presence of this schedule period related positively to schedule growth. In particular the relationship was such that values of schedule growth diminished slightly with longer as planned schedule durations. Therefore, it appears that projects that forecast long design and construction durations are likely to experience slightly less schedule overruns holding the presence of other variables fixed.

Four variables accounted for a lower level of variation and therefore had a lesser impact on schedule growth performance. These variables include:

1. Procurement method,
2. Level of new construction,
3. Commercial terms, and
4. The availability of qualified pool of contractors.

Direct selection of project players had a positive affect on schedule growth. This method of *procurement* was the only one exhibiting a relationship with schedule growth. An indication of how procurement affects schedule performance is seen by the presence of the last variable in the model. The *availability of a qualified pool of contractors* had a negative affect on schedule growth.

Commercial terms such as lump sum for the design team and selecting the construction team using a negotiated process had a positive relationship with schedule growth in one particular area. When the designer held a lump sum contract with the owner, schedule growth values decreased. This variable is insignificant standing alone, however it does indicate the strength and direction of the relationship between it and schedule growth.

Projects classified as *new construction* experienced decreased levels of schedule growth compared renovation projects. While the presence of new construction is recognized in this model, its individual significance in explaining schedule growth performance is very low.

Whether or not a project was submitted from the industry during the original sampling or as part of the non-response study had no significant bearing on the model for schedule growth.

6.8 SUMMARY OF MULTIVARIATE RESULTS

Multivariate linear regression provided an effective method to compare project delivery systems. Regression adjusted direct project delivery comparisons by considering data from each variable that was collected in this research. Five separate models were built. Unit cost, construction speed and delivery speed represent primary results or areas of greatest certainty. Cost and schedule growth models represent areas of less certainty. This analysis identified several variables that consistently affected project performance. Delivery system and facility type were each among the list of variables that explained the greatest proportion of variation within performance models.

6.9 COMPARISON OF MULTIVARIATE TO UNIVARIATE RESULTS

Figure 6.18 illustrates the relationship between facility type, delivery system and the performance metrics used throughout the multivariate analysis. Figure 6.18, when compared directly to Figure 6.16, indicates that multivariate results differ from univariate results. For instance, by investigating the same performance metrics for which multivariate models were developed, Figure 6.16 identified 8 areas where the facility type was a significant variable. However, Figure 6.18 indicates that facility type explained nine areas, some of which are different. For example, on a univariate basis

(Figure 6.16), facility type alone did not explain significant differences in construction speed between the systems used to deliver complex office facilities. However, on a multivariate basis, the complex office facility class was a significant variable in describing the difference between delivery system performance when all other explanatory variables were held constant. This illustrates the ability of regression to identify what is causing the variation in performance. This finding also indicates that the presence of other explanatory variables identified through regression, besides that of facility and owner type, have affected project performance. Therefore, neglecting to adjust for other variables would have resulted in incomplete conclusions. The comparisons and results presented in Figure 6.18 are considered more powerful because they adjust for each variable considered in this research.

A further investigation of Figure 6.18 suggested that unit cost and cost growth were unaffected by the type of facility. Cost growth may be unaffected due to high uncertainty in the model. Unit cost however, had two areas, although not significant, where differences are worth mentioning. First, construction management at risk (p-value of 0.067) was less than design-bid-build in the multi-story dwelling class. Second, design build (0.065) was less than design-bid-build in the high technology facility class. Schedule growth indicated a significant difference between construction management at risk (0.048) and design-bid-build in the simple office facility class. Design-build (0.0) and construction management at risk (0.001) resulted in less schedule growth in the complex office class than design-bid-build.

Speed models indicated the most frequent areas of significance. Besides the significant construction speed differences called out, other notable areas were discovered. Construction management at risk (0.071) was greater than design-bid-build in the complex office group. In the same class, design-build (0.093) had greater speed than did construction management at risk. One difference was also noticed in delivery speed comparisons. Design-build (0.06) was outperforming design-bid-build on high technology projects.

Metric Facility Type	Unit Cost	Construction Speed	Delivery Speed	Cost Growth	Schedule Growth
Light industrial	○	DB, CMR > DBB ●	DB, CMR > DBB ●	○	○
Multi-story dwelling	○	○	○	○	○
Simple office	○	○	DB > DBB, CMR ●	○	CMR < DBB ●
Complex office	○	DB > DBB ●	DB > DBB, CMR ●	○	DB, CMR < DBB ●
Heavy manufacturing	○	○	○	○	○
High technology	○	DB > DBB ●	DB > CMR ●	○	○

Legend

Significant differences called out	< or >
No significant differences between systems	○
Significant differences	●

Figure 6.18: Matrix of significance by facility type adjusted for all explanatory variables.

6.10 SUMMARY

Results presented in this chapter describe measured differences between construction management at risk, design-build and design-bid-build. Each performance metric was analyzed through univariate significant testing sorted by system, facility type and owner type. This procedure identified specific areas where delivery systems were performing significantly different. Furthermore, performance measures for cost and schedule were investigated through the development of mulitvariate linear regression models. Considering all variables collected in this study, and holding the effects of delivery system fixed, direct measurements of certainty, explained variation and the quantity of differences between systems were introduced. Multivariate results were explained as primary, where a very high degree of statistical confidence was present, and secondary, where a reduced level of statistical confidence was present. These distinctions provide an important perspective to the logical application of these results.

CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

This chapter presents the main findings, contributions and limitations of this research. It then acknowledges the limitations of this research. The development of the data collection instrument, research methods and data analysis, and multivariate linear regression are discussed. Observations and lessons learned from this research are presented. Finally, an outline for future research precedes the conclusions.

7.1 SUMMARY OF MAIN FINDINGS

In order to investigate the cost, schedule and quality differences between three project delivery systems, a project delivery framework (Figure 3.1) was developed. This framework was based on the factors listed by the literature and identified by the taskforce as those impacting project delivery performance. Portions of this framework were investigated to compare specific differences between project delivery systems. This research used data from 351 US general building projects to compare design-bid-build, design-build and construction management at risk. Six facility classes, included in this sample, were created via a facility classification process. These classes were light industrial, multi-story dwelling, simple office, complex office, heavy industrial and high technology projects. A strict data collection, verification and analysis process ensured the validity of this collected data.

Project data was first analyzed on a univariate level to investigate several relationships described by the literature. First, looking only at the delivery system used, design-build significantly outperformed design-bid-build in every area except unit cost, intensity and environmental system quality. Design-build also significantly outperformed construction management at risk in the areas of delivery speed and in turnover quality. Construction management at risk significantly outperformed design-bid-build in the areas of cost growth, schedule growth, delivery speed, start up quality, call back quality and the interior space and layout quality. In no case did design-bid-build significantly outperform the other two systems.

Based on these findings, project data was then analyzed on a univariate basis for each of the six specific facility classes and again for two owner types. These results, introduced in Figure 6.16 and Figure 6.17 respectively, indicated that variables other than the project delivery system impacted facility delivery performance. Therefore, a multivariate analysis was performed.

Multivariate analysis offered a more complete explanation of project delivery comparisons because it considered each explanatory variable identified in the project delivery framework. Five multivariate linear regression models were developed. Using the data from all projects, these models identified key variables that impacted facility delivery performance. Based on these models, the following measured differences were found between design-bid-build, design-build and construction management at risk.

Design-build *unit cost* was at least 4.5% less than construction management at risk and 6% less than design-bid-build. In addition, construction management at risk unit cost was at least 1.5% less than design-bid-build. This model explained 99% of the variation in unit cost.

Design-build *construction speed* was at least 7% faster than construction management at risk and 12% faster than design-bid-build. In addition, construction management at risk construction speed was at least 6% faster than design-bid-build. This model explained 89% of the variation in construction speed.

Design-build *delivery speed* was at least 23% faster than construction management at risk and 33% faster than design-bid-build. In addition, construction management at risk delivery speed was at least 13% faster than design-bid-build. This model explained 88% of the variation in delivery speed.

Multivariate results showed significant differences between the three project delivery systems. Several key explanatory variables, which consistently impacted project performance, were identified. They included:

1. Facility type,
2. Facility size,

3. Delivery system,
4. Percent design complete prior to engaging constructor,
5. Team communication,
6. Team experience, and
7. Project complexity.

These models were also used to investigate the impact facility type had on performance while considering all other explanatory variables. This relationship was introduced in Figure 6.18 and showed that facility delivery performance varied by project delivery system and facility type. This finding suggests very strongly that owners may be able to select a project delivery system that performs better for a certain metric for a proposed facility.

This research has clearly shown that there are differences between these systems. Design-build offers more speed and more certainty in cost and schedule than does design-bid-build. However, design-build may not be suited for every situation or each facility type. Likewise, construction management at risk offers more speed than does design-bid-build. It is understood that design-bid-build may be better suited for specific projects, yet it did not offer superior performance on a repeatable basis in any area measured by this research.

7.2 CONTRIBUTIONS OF THE RESEARCH

This research achieved the objectives set forth in section 1.2 and has made several contributions. These include:

1. The first comprehensive comparison of principal US project delivery systems was completed.

The scope of this research included six facility types, private and public owners and the three delivery systems most frequently employed in the US industry. The research utilized data from 351 projects collected from over 100 different companies, agencies and organizations.

2. A data collection instrument was developed to obtain quantitative cost, schedule and quality data from general building projects.

A carefully drafted data collection instrument to obtain empirical data on project performance was developed and tested. This instrument was based on a combination of variables presented in a project delivery research framework. The data collected was used to calculate project performance metrics. Collection, verification and analysis procedures effectively adjusted for bias introduced by using this data collection method.

3. Survey research methods, such as testing for non-response, were successfully applied to improve the validity of data used in this research.

The additional project data, obtained from a small sample of non-respondents, greatly improved the accuracy of research results. The researcher was able to validate the fact that collected data was representative of the industry from which it was drawn.

Of equal importance to future research in this field, a benchmark of likely response has been established. Researchers pursuing similar objectives, with similar scope, using similar methods, can expect that nearly 30% of the industry population which they solicit for data is likely to be inappropriate for study. Therefore, a more accurate representation of sample size, population size and non-response bias can be predicted for similar studies.

4. Multivariate linear regression models were developed and used to compare three project delivery systems.

Significant differences between delivery system performance were discovered. Multivariate analysis adjusted results for all variables collected in this research. Models for performance metrics also indicated the influence particular explanatory variables had on overall project performance. This method identified these critical variables and described their specific relationship with the response variable. Identifying relationships between these variables offered a more complete understanding of project performance. Similarly, separating the effect of project delivery from other potential explanatory variables, such as facility type, gave an accurate account of its individual effect on project performance.

5. This research learned lessons from earlier project delivery research and in turn added to the literature.

Table 6.1 illustrates the attributes of recent project delivery studies and compares them to this study (number six).

	Project Delivery Studies					
Attributes	**1**	**2**	**3**	**4**	**5**	**6**
Data Collection Instrument						
Objective data	*		*		*	*
Owner quality data			*			*
Systems Compared						
CM at risk					*	*
Design-build	*	*	*	*	*	*
Design-bid-build	*	*	*	*	*	*
Partnering	*					
Combination	*					
Type of Comparison						
Univariate analysis	*	*	*	*	*	*
Multivariate analysis			*			*
Number of variables	4	15	45	7	33	58
Survey Research						
Project/ respondent specific data collection	*	*	*	*	*	*
Non-response study						*
Opinion poll		*		*		
Empirical measures	*		*		*	*
Private sector			*	*	*	*
Public sector	*	*	*	*	*	*
Facility classification			*			*
Number of projects	209	NA	332	NA	106	351
Number of subjects	NA	88	NA	108	NA	NA

Table 7.1: Comparison of project delivery study attributes.

In Table 7.1, stars indicate the inclusion or presence of certain attributes in each study. All six studies considered the design-build delivery system, however, only studies three and six analyzed project data on a multivariate basis. Each study is identified below.

1 Alternative approaches to Projects: Better or Worse? (Pocock and Liu, 1996).
2 Appropriate Public Sector Characteristics for Public Sector Design-Build Projects. (Molenaar, 1995).
3 Designing and Building a World-Class Industry. (Bennett, Pothecary and Robinson, 1996).
4 Selecting Design-Build: Public and Private Sector Owner Attitudes. (Songer and Molenaar, 1996).
5 Early Warning Signs of Project Changes. (Oberlender and Zeitoun, 1993).
6 A Comparison of United States Project Delivery Systems. (This research project).

This research benefited greatly from the work of these researchers. Their work identified several variables known to impact the facility delivery process. In addition, the methods, procedures and lessons learned from these researchers provided valuable input to this comprehensive, empirical analysis of the US construction industry.

A direct comparison to the University of Reading's main findings (section 2.3.2) shows similar results. In their study, design-build was found to have an average unit cost 6% less than design-bid-build, and was 12% and 33% faster than design-bid-build in terms of construction speed and delivery speed respectively. In addition, several similar explanatory variables were used to build multivariate linear regression models in both studies.

7.3 OBSERVATIONS

This research has considered and obtained data on many variables that might effect project performance. It has also discovered several other areas, through respondent interviews, lessons learned and discussions with the industry taskforce, that are likely indicators of project performance. These areas are briefly discussed.

1. Project delivery variations.

The choice of a particular project delivery system may in fact be limited to the services available in a particular market at the time of project advertisement. An owner may be able to choose a desired arrangement, yet the way in which design and construction services are delivered may truly define the executed project delivery system.

One frequent example of this was when a facility owner selected a construction management at risk configuration to deliver a project. However, after the advertisement and selection period, the team behaved as they would under a design-build arrangement rather than construction management at risk. In this case the contractor had management expertise, the ability to perform a large majority of the construction work and had previously teamed with the architect/engineer. The contractor had all the skills of a full service design-build firm less the in-house design, which was being fulfilled by a strategic alliance or joint venture arrangement. Therefore, while the owner engaged a team under one format, the team behaved as if it were contracted under an entirely different set of conditions.

Approximately twenty projects used variations of common project team structures in defining their projects. These included:

- integrated teams which included the owner, engineering contractor(s) and the construction contractor(s),
- developers acting as owners who provided pure management services and subcontracted design and construction without assuming project risk,
- sophisticated owners with in-house design and management staff who chose to administer contracts for construction only,
- sophisticated design-build subcontractors who led projects in which their specialty scope was the major package,
- design-build arrangements which utilized pre-defined facility designs and did not engage the construction entity until the construction phase, gaining little or no constructability review, and

- design-build arrangements in which a firm had in-house design and construction capabilities yet chose to subcontract nearly all of the construction work.

It seems that various team arrangements and the culture in which they work may more accurately reflect the true definition of the delivery system. One way to describe the various arrangements is to consider the above categories. This simple distinction would better reflect the organizational merits of the system, thus offering a more accurate comparison of project delivery performance.

2. Commercial terms.

This research has shown that project delivery performance is affected by the commercial terms between project team members. However, it is unclear how the development of these terms relates to project performance. It seems that the time at which lump sum or GMP agreements are set is important. This is because the level of uncertainty which exists at the 10-30% design complete stage, regardless of the facility type, allocates a great deal of risk in the agreement between the owner and bidder. As designs become more certain, costs may become more firm. Therefore, setting project costs early may initiate long term growth in cost if preliminary estimates or projections are inaccurate or do not contain appropriate contingencies.

On the other hand, combinations of commercial terms may diminish the uncertainty of design and more accurately assign project costs. For instance, an owner has the option to engage an architect or builder early to advance facility planning and design to a well defined stage under a cost plus or reimbursable agreement. At that point, the builder has a much better opportunity to understand the facility, solicit subcontract bids from the industry and forecast realistic costs for the remainder of facility design and the subsequent construction phase. This allows the owner to negotiate a final lump sum or GMP based on a firm understanding of the project, one which theoretically should not grow in scope, time or cost.

3. Percent design complete when construction entity joins the team.

The benefit of having early constructor input or to having a team well suited to handle changes was only realized when the owner had the capability to manage an integrated, team based approach. By definition, design-build projects generally gained construction input very early, engaging the construction entity when little design was complete.

4. Portions of the general building sector were inappropriate for this study.

The non-response study showed 29% of respondents were out of the research scope. This would be a realistic expectation for the total sample. This is more than four times the amount indicated through phase one data collection results. Because it has never been studied, this finding is significant and will improve the ability of other researchers to accurately predict response in studies of similar scope using similar data sources and methods.

7.4 LIMITATIONS OF THE RESEARCH

This research has five limitations which are recognized.

1. Several other variables that may potentially influence project performance are identified.

This research created seven performance metrics to compare three project delivery systems. Critical data on cost, schedule and quality was collected to calculate these measures. In addition, over sixty explanatory and interacting variables were recorded for each of 351 projects. This achievement yielded significant results. However, other variables may affect project performance in meaningful ways. Some of these variables were discovered during data collection and analysis phases, others were deemed difficult for the project respondent to collect during the development of the data collection instrument. Therefore the nature of this research prohibited the inclusion of all potential variables. Three of these variables are described below.

Modifications to the contract were not systematically recorded. Changes in scope were specifically identified on certain projects, while others included them in final cost and gross square footage values. A more appropriate approach requires the respondent to reveal all owner initiated changes which changed the scope of work, altered the final price or created an extension or compression of time. This would standardize projects through the comparison of complete contract characteristics. Tracking this type of variable demands an extensive amount of data from each respondent and a thorough explanation of what constitutes a change.

Timing of modifications to the contract allows the researcher to record how a particular delivery system handled change during the life of a project. Information about this variable can be obtained if modifications are recorded regularly. Together, these data points indicate the stage when changes are likely to occur, the magnitude of these changes and the ability of each delivery system to handle or recover from such changes.

The *existence of specialty subcontractors* on a project team was not considered. The manner in which major scopes of work such as mechanical, electrical and plumbing packages are designed and constructed indicates a dimension of the team not included in generic project delivery systems. For instance, trades such as mechanical or electrical can be 60% of the total project scope in the high technology market. When this occurs, many specialty or design-build subcontractors may play a significant role in or lead project design and construction activities, thus changing the roles of project participants.

2. Comparisons only consider the design and construction processes.

Owner driven processes such as planning, management, advertisement, procurement and administration were not included in the study. Although accurate comparisons have been made regarding the base building, these factors may provide a more complete view of project performance. Using transaction cost theory, Lynch (1996) developed models to demonstrate the relationships between the project delivery system being used and the project level costs. He found that accurately capturing specific owner costs to execute and administer contracts was extremely difficult.

3. Quality data was recognized as the least objective data collected for performance measurement.

Objective data for quality performance was collected by direct interaction between the researcher and facility owner. However, quality was still based on the perception and original expectation of the owner. Furthermore, varying levels of expectations are generally associated with different delivery systems. For instance an owner who expects very little from the project delivery process may be very surprised by the final product. Therefore, because the owner had such low expectations, even a marginal job has the potential to receive exceptional quality scores from the owner.

Likewise the age of a facility may effect the perception of its quality. It is expected that an owner's perception of a facility's quality may change over the life of the facility. This research used projects ranging from 1 to 7 years in operation. Therefore, a variety of durations may be playing a part in determining project quality.

4. Quality was analyzed on a univariate level.

The nature of quality data was less objective than other principal metrics. It asked facility owners to rate performance on a fixed scale, such as low, medium or high. The probability that an owner would respond 'high' to a specific question may be greatly affected by more qualitative variables such as prior expectations or bad experiences. These variables were not collected. Therefore, quality comparisons were difficult on a multivariate basis. Corbett (1997) recognized this difficulty as well. She used a Quality Index and a Quality Grade as a means of quantifying quality on 21 completed industrial projects.

5. Project timelines for project delivery systems are different.

Many project delivery variations were recognized in this research. In particular, project timelines as they relate to specific project delivery systems indicated that certain comparisons between the systems are unclear. For instance, the time it takes to prepare for design-build and design-bid-build jobs may be different. In one case of design-bid-build, it was reasonable to expect that very little design was completed prior to selecting the design team. Therefore, the design start date (0% design complete) provided by project respondents was likely to reflect the date when design actually started. On the other hand, an owner may choose to work through programming and conceptual design (0-20% complete) with a select design team prior to advertising and selecting the design team who will ultimately complete the design. These cases may also exist in design-build. For instance, the design start date provided by the project respondent may reflect the date from which design was at zero percent complete. Or, it is possible that certain design-build projects had substantial design completed during the development and response to proposals as part of the competitive selection process. In this case, a design start date, may have been before the design-build entity was selected.

These scenarios are examples of the inconsistent anecdotal evidence that was found within this research. The data necessary to clarify these questions was asked of owners and other project respondents, however, these dates were unrecorded or unknown to the owner.

7.5 FUTURE RESEARCH

The models developed in this research were used effectively for multivariate comparisons. These models offer an advanced approach to describing relationships among variables and have shown the strength of these relationships. Each model has the capability of prediction. However, levels of certainty in some cases may prohibit their actual application. Improved analysis for this purpose may foster more advanced models that could be introduced to the industry as forecasting tools.

The next logical step to improve analysis is to take the lessons learned from this thesis and focus comparisons by holding critical variables fixed. This will allow the researcher to consider a wider range of variables specific to a particular market. Using the methods described in this research, a similar study should target a particular facility class, delivery system and principal team member for analysis. These areas were consistently recorded as the top variables influencing project performance and therefore are the obvious choice for a more defined investigation. Four specific studies are proposed.

1. Build predictive models for design-build, high technology projects that require specialty contractor expertise.

The high technology facility class is well represented in this study and represents the highest project complexity and cost. Furthermore, the high technology market has grown in the past five years, thus making it a viable and important class to target. In addition, the high technology market is characterized by intense schedule demands, the existence of specialty teams and very stringent quality standards that are often fulfilled using the design-build system. This more focused study should target one specialty trade on high technology, design-build projects. Mechanical specialty contractors usually have the largest single portion of the work. These contractors may have the in house capability to design, fabricate and install very complex packages of work. Many of these also have the capability to lead major high technology projects.

This study should consider projects within the high technology market in the United States. It should measure cost, schedule and quality performance of representative project delivery systems. Tenant and process work should not be included in cost and schedule data for comparison. Other quantitative factors, beyond those described in this research, which may be specific to the high technology market, should be considered during the data collection phase. Project schedule measures should include at least the as planned and as built dates for design and construction. Likewise, costs should include contract and final costs for design and construction. This will allow a direct comparison to the 61 high technology projects considered in this research.

2. Empirically compare modes of public sector delivery system performance.

This research has very broadly recorded public and private owner types. However, within the public sector a variety of agencies are operating under very different regulatory constraints. For instance, federal organizations such as the department of defense have more restrictions for selecting teams and delivery systems than do state governmental agencies. Therefore, being able to keep specific owner types constant may eliminate a great number of variables possibly affecting project performance. An immediate, natural division of public sector projects should separate federally owned jobs from those procured at the state and local level. These jobs can then be directly compared to similar private sector projects. The comparison should be made in the multi-story dwelling and simple office facility classes. The majority of data collected from the federal sector projects were within these two classes.

3. Investigate the role of specialty subcontractors on design-build projects.

Subcontractor experience with delivery systems and facility types was identified as a critical indicator of project performance in this research. Therefore, the role of the subcontractor should be more closely analyzed. Using data specifically obtained from a single specialty trade will allow the researcher investigate the role and impact of one particular team member holding the effect of project delivery system fixed. One such study is to identify key factors that cause success for electrical subcontractors on design-build projects (Sanvido, 1996). This project is analyzing empirical project data to explain the current role and success factors of electrical subcontractors in the design-build market. This study could be replicated for other specialty contractors.

4. Identify the impact of minority subcontractors on publicly funded projects.

The public sector has made a concentrated effort to expand the capacity of minority subcontractors by establishing participation requirements on public projects. However, many of these subcontractors are unable to handle the extreme fluctuations in work scope or employee requirements often initiated by such requirements. This fact makes certain subcontractors unstable. The first focus should establish the different classes of small business and minority subcontractors. Next their role in the public sector should be investigated to identify the impact their presence has on project performance. Finally, a comparison should be made between the small business and minority organizations found in the public sector to those succeeding in the private sector.

7.6 CONCLUSIONS

The construction industry has made substantial efforts to expand project delivery research in the past decade. However, at the beginning of this thesis it was clearly stated that an objective comparison of project delivery systems had never been made. This thesis first offered a project delivery research framework that categorized the major decisions and variables that exist in the facility delivery process. Based on the organization of the project delivery framework, this thesis offered a performance-based, empirical investigation of the three principal delivery systems used in the US construction industry today. All of the study objectives were met.

Methods uncommon to the construction research arena, such as a large-scale data collection process, extensive data checking, non-response verification, univariate hypothesis testing and multivariate regression analysis were utilized. The execution of these methods provided significant conclusions about industry performance. It is recognized that this research is the first to target the US construction industry in this way. For this reason, the researcher has shown areas where this study is limited and offers avenues to build upon this foundation. To do this, the researcher believes that the education and participation of the industry to the identified state of performance is paramount. This research has utilized data specifically drawn from the US construction industry. Therefore, the results of this research must first be presented to the industry to establish a performance benchmark for project delivery systems. After educating the industry on its performance, the evolution of design and construction services and its players can be effectively researched, developed and managed.

This project has shown that a collaborative environment between the construction research community and industry can foster the advancement of project delivery research. In particular, alliances between universities, corporations and trade organizations can promote the execution of the future research directions described in this chapter. These directions are driven primarily by owner dissatisfaction with the delivery process and their education using specific performance data. Progressive organizations are accommodating change by offering more services in areas such as real estate, long term facility management and project financing. Additionally, technically advanced specialty contractors are becoming more and more common, leading projects in certain markets. The structural change in the industry will demand a more focused balance of education, research and application by industry/ university partnerships.

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APPENDIX A

PROJECT DELIVERY SYSTEM DATA COLLECTION INSTRUMENT

PROJECT DELIVERY SYSTEM SURVEY

THE CONSTRUCTION INDUSTRY INSTITUTE
THE PENNSYLVANIA STATE UNIVERSITY

INSTRUCTIONS

Penn State has been selected to conduct a national survey of the three principal project delivery systems in the U.S. today. Please help us by completing the survey for at least one project you have completed in the last 5 years in the U.S. You may submit up to ten. At your request we will provide you a copy of the survey results.

Each survey form should be coordinated by your Project Manager. Thorough responses to survey sections 1 to 5 are the most critical to this study. Other sections are important to explain the reasons for the measured differences.

Upon receipt of your data, Penn State will number each copy, remove company identification, and remove project identification. The information you provide will be kept in strict confidentiality.

Please return the completed questionnaire by mail or fax before Dec. 31, 1996 to:

Dr. Victor E. Sanvido, Dept. of Architectural Engineering, Penn State
University, 104 Engineering Unit "A", University Park, PA 16802-1416
Fax: (814) 863-4789 Phone: (814) 865-2869

DEFINITIONS

Design Bid Build is a traditional process in the US construction industry where the owner contracts separately with a designer and a contractor. The owner normally contracts with a design company to provide "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.

Design Build is an 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.

In **CM at Risk**, the owner contracts with a design company to provide a facility design. The owner separately selects a contractor to perform construction 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.

SECTION I: PROJECT CHARACTERISTICS

Project name: Project location: ____________

Project executive/ respondent who provided data: ____________________

Phone number: ____

Company name: ______________________________________

○ Owner ○ Design-Builder ○ Architect/Designer ○ Contractor

Please mark the appropriate oval for project type:

- ○ Office
- ○ Schools
- ○ Recreation
- ○ Housing
- ○ Light Manuf.
- ○ Warehouse
- ○ Grocery
- ○ Postal
- ○ Micro-Elec.
- ○ Pharmaceutical
- ○ Food Proc.
- ○ R & D
- ○ Parking
- ○ Other

Building gross square footage sf No of floors ____________

Percentage of the project: Renovation % New construction ______ %

SECTION II: PROJECT DELIVERY SYSTEM

Mark the appropriate oval for the project delivery system which best suits that used on your project:

Construction Management @ Risk	○
Design-Build	○
Design-Bid-Build	○

Mark the appropriate oval for the commercial terms used for the design-builder or designer and contractor: (*If Cost plus, please state fee type in blank provided*)

Design-Builder	○ Lump Sum	○ Cost Plus___Fee	○	GMP
Architect/Designer	○ Lump Sum	○ Cost Plus___Fee	○	GMP
Contractor	○ Lump Sum	○ Cost Plus___Fee	○	GMP

SECTION III: PROJECT SCHEDULE PERFORMANCE

Please provide the following **schedule** information:

Item	As Planned (mm/dd/yy)	As Built (mm/dd/yy)
Date Project was Advertised		
Design Start Date (Notice to Proceed)		
Construction Start Date (Notice to Proceed)		
Construction End Date (Substantial Completion)		

SECTION IV: PROJECT COST PERFORMANCE

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

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

Please estimate the cost of site work (work done outside the footprint of the building) as the percent (%) of final construction costs: ______________ %

SECTION V: PROJECT QUALITY PERFORMANCE

If you are the owner, please complete section V. If not, please provide the owner's name or point of contact ________________________________
and phone number ____________________, *and proceed to survey section VI.*

Mark the appropriate ovals to evaluate the **quality** of the building:

Difficulty of facility startup:
○ High ○ Medium ○ Low

Number and magnitude of call backs:
○ High ○ Medium ○ Low

Operation/maintenance cost for building/site:
○ High ○ Medium ○ Low

Did the quality of envelope/roof/structure/foundation meet your expectations?
○ Exceeded ○ Yes ○ No

Did the quality of interior space/layout meet your expectations?
○ Exceeded ○ Yes ○ No

Did the quality of environmental systems (light,HVAC) meet your expectations?
○ Exceeded ○ Yes ○ No

Did the quality of process equipment/layout meet your expectations?
○ Exceeded ○ Yes ○ No

SECTION VI: PROJECT TEAM CHARACTERISTICS

Mark the appropriate oval for each of the following attributes of your project team:

Project team selection:

○ Open Bidding	○ Prequalified Bidding
○ Negotiated Contract	○ Contract Documents

Ability to restrain contractor pool:	○ High	○ Low
Was there a pool of qualified contractors?	○ Yes	○ No

What percentage of design was complete when the construction entity joined the project team? ____________ %.

Individual experience of members with similar facilities:

Owner's Representative	○ Excellent	○ Limited	○ None
Design-Builder	○ Excellent	○ Limited	○ None
Architect/Designer	○ Excellent	○ Limited	○ None
Contractor	○ Excellent	○ Limited	○ None
Subcontractors	○ Excellent	○ Limited	○ None

Individual experience of members using your project's delivery system:

Owner's Representative	○ Excellent	○ Limited	○ None
Design-Builder	○ Excellent	○ Limited	○ None
Architect/Designer	○ Excellent	○ Limited	○ None
Contractor	○ Excellent	○ Limited	○ None
Subcontractors	○ Excellent	○ Limited	○ None

Team's prior experience as a unit:	○ Excellent	○ Limited	○ None
Project team communication:	○ Excellent	○ Limited	○ None
Project team chemistry:	○ Excellent	○ Adequate	○ Poor
Owner type:	○ Public	○ Private	
Owner-project team relationship:	○ First Time	○ Partnering	○ Repeat
Owner representative's capability:	○ Excellent	○ Adequate	○ Poor
Owner's ability to define scope:	○ Excellent	○ Adequate	○ Poor
Owner's ability to make decisions:	○ Excellent	○ Adequate	○ Poor
Project complexity:	○ High	○ Average	○ Low
Regulatory/legal constraints:	○ Many	○ Few	○ None
Onerous contract clauses:	○ Numerous	○ Several	○ None
Labor type:	Union ___%	Non Union ___%	
Contractor's work split:	Direct Hire ___%	Subcontracted ___%	

SECTION VII: PROJECT DATA

For the following items please mark the appropriate oval in each category to identify the appropriate systems and/or descriptors that apply to your project:

FOUNDATION:

○ Slab on grade with spread footings
○ Caissons, piles or slurry walls
○ Mat foundation
○ Other:

STRUCTURE:

○ 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:

ARCHITECTURAL INTERIOR FINISHES:

○ Minimal (eg. warehouse, factory)
○ Corporate office
○ Monumental building finishes (e.g. marble)
○ Other:
○ Standard commercial office
○ Clean room environment

EXTERIOR ENCLOSURE:

○ All glass curtain wall
○ CMU, brick, or stone
○ Cast-in-place exterior walls
○ Metal panels
○ Precast panels
○ Other:

ROOFING:

○ Asphalt shingle
○ Built-up /single-ply membrane
○ Other:
○ Steep roof with tile/slate
○ Architectural standing seam

HEATING/COOLING:

○ Roof top units
○ Heating only
○ Other:
○ Central plant
○ Cooling only
○ Split system
○ Ventilation only

ELECTRICAL:

○ Uninteruptable power supply
○ General lighting and computer use
○ Process equipment loads
○ Electric heat
○ Intensive computer use
○ Security system

CONTROLS:

○ Direct digital controls
○ Other:
○ Pneumatic controls

SITE:

○ Urban
○ Existing utilities
○ Other:
○ Suburban
○ Existing roads
○ Rural
○ Mass excavation

SECTION VIII: PROJECT SUCCESS CRITERIA

Please list the criteria your organization uses to measure success and then mark the appropriate oval 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

5. ______________________________

○ Excellent ○ Average ○ Poor

Mark the appropriate oval to rate the overall success of the project:

○ Excellent ○ Average ○ Poor

SECTION IX: LESSONS LEARNED

If the answers to any of the following are yes, please list examples or reasons in the space below each question.

List any lessons you learned on this project about the project delivery system:

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

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

Did the project meet the intended needs?

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

APPENDIX B

SUMMARY STATISTICS FOR UNIVARIATE COMPARISON

Variable	Sort	N	Median	Mean	St.Dev.	Q1	Q3
Area	CM@R	80	134441	188158	192565	54595	240750
	DB	155	90877	184969	266760	27000	240000
	DBB	116	91834	213097	366987	32350	208975
Unit Cost	CM@R	80	106	147.9	127.1	79.2	178.5
	DB	155	80	129.6	171	50	144
	DBB	116	120	179.5	299.4	73	166.5
Cost Growth	CM@R	80	3.37	5.537	8.092	0	10.278
	DB	155	2.17	4.48	13.13	0	8.38
	DBB	116	4.83	8.11	10.86	1.69	12.77
Sched Growth	CM@R	80	0	2.81	18.61	-3.95	5.4
	DB	155	0	3.14	17.23	-1.83	9.22
	DBB	116	4.44	9.33	18.38	0	15.57
Const. Speed	CM@R	80	8192	12910	14664	3786	16853
	DB	155	9091	15828	19340	3132	20833
	DBB	116	5135	9763	11388	2063	13921
Delivery Speed	CM@R	80	4712	9017	11332	2537	11788
	DB	155	6842	12370	15893	2301	16438
	DBB	116	3250	6390	8122	1049	7877
Intensity	CM@R	80	4.67	7.35	9.23	3.22	7.25
	DB	155	5.79	9.281	12.26	3.66	10.56
	DBB	116	3.67	7.46	21.03	2.21	5.92
StartUP	CM@R	76	10	7.434	3.511	5	10
	DB	144	10	7.5	3.239	5	10
	DBB	109	5	5.963	3.567	5	10
CallBacks	CM@R	75	10	8.067	2.585	5	10
	DB	141	10	7.943	3.109	5	10
	DBB	108	5	7.037	2.983	5	10
Op&Mnt	CM@R	71	5	6.69	3.267	5	10
	DB	133	10	7.669	2.79	5	10
	DBB	101	5	6.881	3.151	5	10
ERSF	CM@R	70	5	5.357	1.77	5	5
	DB	141	5	5.709	2.434	5	5
	DBB	104	5	4.952	2.362	5	5
InSp&Lo	CM@R	74	5	6.284	2.491	5	10
	DB	144	5	6.146	2.344	5	8.75
	DBB	108	5	5.185	2.361	5	5
Environ	CM@R	74	5	5.338	2.082	5	5
	DB	144	5	5.243	2.731	5	5
	DBB	106	5	4.858	2.436	5	5
Eq&Lo	CM@R	40	5	5.625	2.022	5	5
	DB	107	5	5.607	2.14	5	5
	DBB	71	5	5.07	1.981	5	5

Table B.1: Sample statistics by delivery system.

Variable	Sort	N	Median	Mean	St.Dev.	Q1	Q3
Area	1	98	183780	253603	280262	76646	322625
	2	27	111000	149300	165885	72700	175000
	3	84	45000	98541	155033	21463	108750
	4	64	106500	279990	388594	50000	295828
	5	17	140000	183197	206388	22705	292500
	6	61	84500	167981	347026	45005	196500
Unit Cost	1	98	56	105.3	246.5	30	87
	2	27	100	101.7	45.74	59	124
	3	84	106	118.75	73.6	68.75	146.75
	4	64	110.5	134.2	110.4	78.3	165.5
	5	17	134	173.1	198	73	233.5
	6	61	189	294.9	336.6	130	311
Cost Growth	1	98	3.85	7.99	14.39	0.43	11.03
	2	27	3.79	6.57	12.04	0.78	10.57
	3	84	2.3	3.96	10.7	0	7.45
	4	64	2.855	3.951	7.351	-1.223	8.985
	5	17	2.77	6.3	11.17	-1.12	14.11
	6	61	3.3	6.98	10.29	0	10.9
Sched Growth	1	98	0	4.83	20.31	0	10.38
	2	27	5.39	12.4	27.32	-0.43	21.17
	3	84	0	3.84	13.65	0	7.98
	4	64	0	4.29	17.56	-2.09	7.83
	5	17	1.98	8.9	22.35	-0.18	10.03
	6	61	2.09	3.9	13.4	0	11.78
Const. Speed	1	98	17805	23456	22268	7561	29801
	2	27	5966	8441	7839	4031	9403
	3	84	4410	6691	7071	1988	9251
	4	64	8269	13247	15318	3238	18822
	5	17	15591	14319	11757	2046	24829
	6	61	4832	7192	8576	2737	9348
Delivery Speed	1	98	13518	17976	17916	4383	22455
	2	27	4257	5718	5892	2274	6030
	3	84	2661	4404	5074	1180	5550
	4	64	5506	9534	12766	2059	13348
	5	17	10513	10785	9713	1664	18732
	6	61	3744	4927	6092	1513	5278
Intensity	1	98	3.89	5.43	6.837	2.368	6.583
	2	27	3.21	4.358	3.528	2.5	4.59
	3	84	5.255	6.77	5.751	3.298	8.195
	4	64	4.235	7.072	7.402	2.842	8.428
	5	17	7.43	14.45	20.87	4.5	13.62
	6	61	6.14	15.99	30.89	3.63	15.51

Table B.2: Sample statistics by delivery system and facility type.

Variable	Sort	N	Median	Mean	St.Dev.	Q1	Q3
StartUP	1	88	10	6.989	3.518	5	10
	2	27	5	6.481	3.344	5	10
	3	80	10	7.875	2843	5	10
	4	61	10	7.377	3.489	5	10
	5	16	5	6.875	3.096	5	10
	6	57	5	5.526	3.974	0	10
CallBacks	1	88	10	8.239	2.738	5	10
	2	27	5	6.296	2.972	5	10
	3	76	10	7.303	3.311	5	10
	4	60	10	8.167	2.598	5	10
	5	16	10	8.75	2.236	6.25	10
	6	57	5	7.105	3.126	5	10
Op&Mnt	1	80	10	7.625	3.079	5	10
	2	22	5	6.818	2.462	5	10
	3	74	5	7.297	2.642	5	10
	4	58	5	6.724	3.183	5	10
	5	16	10	8.75	2.236	6.25	10
	6	55	5	6.545	3.594	5	10
ERSF	1	86	5	5.349	2.274	5	5
	2	26	5	4.808	1.721	5	5
	3	76	5	5.263	2.435	5	5
	4	58	5	5.517	2.234	5	5
	5	17	5	6.176	2.186	5	7.5
	6	52	5	5.481	2.477	5	5
InSp&Lo	1	83	5	5.422	2.369	5	5
	2	27	5	5.185	1.688	5	5
	3	81	5	5.988	2.672	5	10
	4	61	5	6.393	2.438	5	10
	5	17	5	5.882	1.965	5	5
	6	57	5	6.053	2.453	5	7.5
Environ	1	84	5	4.94	2.514	5	5
	2	27	5	4.444	2.532	5	5
	3	81	5	5.123	2.736	5	5
	4	59	5	5.424	2.328	5	5
	5	17	5	5.882	1.965	5	5
	6	56	5	5.268	2.416	5	5
Eq&Lo	1	63	5	5.317	1.767	5	5
	2	12	5	5	0	5	5
	3	46	5	5.109	1.663	5	5
	4	39	5	5.641	2.045	5	5
	5	14	5	5.357	2.373	5	5
	6	44	5	5.909	2.908	5	10

Table B.2 continued: Sample statistics by delivery system and facility type.

Variable	Sort	N	Median	Mean	St.Dev.	Q1	Q3
Area	Public	151	90000	221522	364455	33400	240000
	Private	200	100000	174962	216448	40000	228000
Unit Cost	Public	151	124	167.2	234.8	89	168
	Private	200	79.5	137.5	199.2	52.3	150.8
Cost Growth	Public	151	4.31	7.251	10.878	0.63	11.1
	Private	200	2.24	4.918	11.851	0	9.41
Sched Growth	Public	151	2.09	5.29	17.85	0	10.97
	Private	200	0	4.98	18.38	0	7.89
Const. Speed	Public	151	5625	10614	13956	2183	12998
	Private	200	9522	15079	17511	3371	19807
Delivery Speed	Public	151	3820	7599	11238	1213	8735
	Private	200	6099	11163	14008	2185	13920
Intensity	Public	151	4.16	6.29	7.957	2.75	6.6
	Private	200	5.33	9.71	18.83	3.04	9.76
StartUP	Public	145	5	6.828	3.375	5	10
	Private	184	10	7.092	3.56	5	10
CallBacks	Public	141	5	7.092	2.997	5	10
	Private	183	10	8.115	2.894	5	10
Op&Mnt	Public	131	5	7.023	2.827	5	10
	Private	174	10	7.299	3.208	5	10
ERSF	Public	142	5	5.211	2.218	5	5
	Private	173	5	5.52	2.354	5	5
InSp&Lo	Public	143	5	5.594	2.41	5	5
	Private	183	5	6.066	2.422	5	5
Environ	Public	141	5	4.858	2.386	5	5
	Private	183	5	5.355	2.57	5	5
Eq&Lo	Public	91	5	5.275	1.88	5	5
	Private	127	5	5.551	2.203	5	5

Table B.3: Sample statistics by delivery system and owner type.

APPENDIX C

MULTIVARIATE REGRESSION – TECHNICAL RESULTS

Technical procedures are described for each model developed in this research. Variable selection processes are summarized, complete regression analysis is presented and diagnostic tests are discussed. Regression output is used to investigate model performance, the significance of individual variables and their relationships to dependent or performance measures.

C.1 UNIT COST

Unit cost was defined as the gross square footage divided by the final project cost. Using all possible explanatory variables, best subset algorithms were made. These tests included all sensible and possible predictor variables. This form of multivariate regression tests each variable for its possible inclusion in the model. It was desirable to use only the variables known prior to the start of design and construction. This allowed the researcher to calculate performance results from information known prior to project start. The number of possible predictors considered was extremely high, approximately 100, after making all necessary indicator and interacting variables. However, the maximum number of free predictors handled by Minitab® on any given attempt is 20. Therefore, variables were considered in a random fashion to create all potential subsets. This initial screening of variables was critical to the success of each model because it very quickly identified the relative impact of a large set of variables upon performance measures. Models with the highest proportion of explained variation (R-Sq) and the Mallow's C-p value nearest that to the number of variables included in the best subset were explored. A model fitting the data well would have a C-p value nearly equal to the number of variables being considered (Neter, 1996). The final best subsets regression is shown in Figure C.1. Initially, contract unit cost, project delivery, facility type and particular facility systems and commercial terms were explaining nearly all of the variation in unit cost. However, residual diagnostic indicated the need for adjustments.

In conjunction with the best subsets regression, a model for unit cost, similar to that used by The University of Reading, was tested. Many of the above variables were similar and showed positive results. This offered a good starting point for the consideration of variables in the best subsets regressions. This opportunity, to compare models, does not exist for all other response variables because the University of Reading did not report models for cost and schedule growth metrics.

Several models for unit cost were attempted. Each time a model was attempted, variables were checked for their individual significance by investigating T and P values at an alpha of 95%. Additionally, the significance of the variables as a group was tracked using F values and group P values. The group of variables obtained from the best subsets regression were analyzed using the regression function in Minitab®. Residuals were constantly examined during the attempt of each model. This was important to verify the validity of the major assumptions of linear regression. Of these, non-constant variance was most critical. Initially, variance of fitted values was clearly a problem. It was later reconciled through the log transformations of unit cost, area and contract unit cost.

Several interaction variables were included in the model. Of the core variables included, area, project delivery, contract unit cost and facility type interactions were created. Also, interactions between facility systems and each facility type were considered. This allowed the researcher to recognize both the effect of certain variables controlled for other variables and to see if the effect of one variable depended greatly on the varying levels of another predictor variable. For instance, project facility type was affected by certain systems of varying complexities. In other words, the unit cost achieved on a certain type of facility may be more or less depending on the type and complexity of the foundation system used.

With interactions in mind, a closer look at the model residuals was required. Additionally, the residuals were plotted against other predictor variables alone to see if relationships existed that would point to possible transformations. Of the variables being studied, relationships between contract unit cost and project area with final unit cost were non linear. The proper relationship between these variables was achieved using a log transformation with contract unit cost and a weighted log transformation for area. In addition, the log of final unit cost was utilized. Transforming unit cost improved the residual distribution and the variable's individual significance in the model. Although abnormal, these transformations are still relatively simple to explain. For instance, using the log to explain the relationship between final and initial unit cost indicates that values of final unit cost rise exponentially as contracted unit costs increase.

Accounting for several possible transformed variables gained the highest possible level of explained variation, nearly 100%. Contract unit cost, facility type, project size and delivery system were of most significance to this model. Several interaction variables were also discovered. These included the effects of project delivery on facility type and project delivery on project size. Each time a new variable was created, the model was analyzed using regression and verified by investigating residual model diagnostics.

Several added variable plots were attempted to examine the marginal relation of proposed predictor variables given the other predictor variables already in the model. Plots of area and contract unit cost indicated linear bands of points, showing that those considered do belong within a linear model for construction speed.

Cook's influence was used to check for observations exhibiting a high level of actual influence on the models' ability to determine fitted values. Although the values were not extremely large, four observations were clearly apart from other observations. Each of these observations or jobs were analyzed separately. These jobs were extreme outliers, and forced the model to inaccurately adjust for their presence. Two jobs were from the light industrial class, one a heavy industrial facility and another a multi-story dwelling. Each job had unusually high unit cost values. In particular, the fourth project was a large, public prison renovation with a poorly defined scope. These unusual jobs were omitted from the model. Leverage was also used to determine how influential a case was in determining the regression coefficients.

With high actual influence points explained, interactions developed and transformations included, a final model was tested. This model achieved an R-squared value of 99.1%. Figure C.2 shows final regression output for the unit cost model. The residual model diagnostics shown in Figure C.3 indicate the model was performing extremely well. The first graph shows the normal plot of residuals. This line should be and is nearly linear. The second chart of residuals in the upper right corner shows time dependency. This test did not apply to this data as each project was independent, therefore non-independence was not a problem. The histogram in the lower left corner shows a fairly good distribution of residuals, no significant outliers. Finally, testing for constant variance indicated that fitted values were consistent. This was indicated by the random distribution of data points in the graph. The relationship in this graph was severely affected by variables such as unit cost and area. However, transforming these variables allowed the model to track their true relationship to unit cost.

Finally, to measure differences between delivery systems, values for unit cost were calculated using the final model. Values were calculated by developing equations for each possible circumstance by delivery system. This allowed the model to predict values to be used for comparison. This was accomplished by allowing the model to calculate unit costs for each job had it been completed using design-build, design-bid-build and then construction management at risk. Developing descriptive statistics on these values allowed for a direct comparison between the performance of each system.

Main findings show that the unit cost of design-build projects was, on average, at least 6.1% less than design-bid-build and 4.5% less than construction management at risk. In addition, construction management at risk projects were at least 1.5% faster than design-bid-build.

C.2 CONSTRUCTION SPEED

Noted in the discussion of principal metrics, construction speed tracked the square footage of work put in place per month. This represented how quickly the building was erected during the construction period. It is important to keep in mind how critical the design period is which generally happens as preparation for the construction period. A poor effort during design in any area of planning, scope definition, detailing, information communication or material selection can delay construction during the initial startup of operations.

Using all possible explanatory variables, best subset algorithms were made. These tests included all sensible and possible predictor variables. This form of multivariate regression tests each variable for its possible inclusion in the model. It was desirable to use only the variables known prior to the start of design and construction. Doing so allows the researcher to calculate performance results from information known prior to project start. The number of possible predictors considered was extremely high, approximately 100 after making all necessary indicator and interacting variables.

However, the maximum number of free predictors handled by Minitab® on any given attempt is 20. Therefore, variables were included in a random manner to create all potential subsets. This initial screening of variables was critical to the success of each model because it quickly identified the relative impact of a large set of variables upon performance measures. Models with the highest proportion of explained variation (R-Sq) and the Mallow's C-p value nearest that to the number of variables included in the best subset were considered. A model fitting the data well was indicated by a C-p value nearly equal to the number of variables being considered. The final best subsets regression is shown in Figure C.4. Initially, area, contract unit cost, project delivery, facility type, team communication and project complexity were explaining 65.9% of the variation in construction speed.

In conjunction with the best subsets regression, a model for construction speed, similar to that used by The University of Reading, was tested. Many of the above variables were similar and showed positive results. This offered a good starting point for the consideration of variables in the best subsets regressions. The opportunity to compare models did not exist for all other response variables because the University of Reading did not report models for cost and schedule growth metrics.

Several models for construction speed were attempted. Each time a model was attempted, variables were checked for their individual significance by investigating T and P values at an alpha of 95%. Additionally, the significance of the variables as a group was tracked using F values and group P values. The group of variables obtained from the best subsets regression were tested using the regression function in Minitab®. This allowed the researcher to investigate residual model diagnostics. Residuals were constantly examined during the attempt of each model. This was important to verify the validity of the major assumptions of linear regression.

Several models experienced improved levels of R-squared by the inclusion of interaction variables. Of the core variables included, area, project delivery, contract unit cost and facility type interactions were created. This allowed the researcher to recognize both the effect of certain variables controlled for other variables and to see if the effect of one variable depended greatly on the varying levels of another predictor variable. For instance, project facility type was affected by facility area. In other words, the construction speed achieved on a certain facility type may be more or less depending on the square footage of that building.

With interactions in mind, a closer look at the model residuals was required. Additionally, the residuals were plotted against other predictor variables alone to see if relationships existed that would point to possible transformations. Of the variables being studied, contract unit cost and project area were non linear. The proper relationship between these variables and construction speed was achieved using a log transformation with contract unit cost and a weighted log transformation for area. Transforming unit cost improved the residual distribution and the variable's individual significance in the model. Additionally, although abnormal, these transformations were still relatively simple to explain. For instance, using the log to explain the relationship between construction speed and area indicates that values of construction speed rose exponentially as project size increased.

Accounting for several possible transformed variables gained higher levels of explained variation. Facility type, project size and contract unit cost were most significance to this model. Several interaction variables were also discovered. These included the affects of project delivery on facility type and project delivery on project size. Each time new variables were created, the model was tested using regression and verified by investigating residual model diagnostics.

Several added variable plots were attempted to examine the marginal relation of proposed predictor variables given the other predictor variables already in the model. Plots of area and unit cost indicated linear bands of points, showing that those considered do belong within a linear model for construction speed.

Cook's influence distance was used to check for observations exhibiting a high level of actual influence on the models' ability to determine fitted values. Although the values themselves were not extremely large, two jobs were clearly apart from the pack. Each of these jobs was analyzed separately. Both projects were highly complex renovation projects that caused the model to inaccurately track their performance. These unique jobs, having unusual circumstances, were omitted from the model. Leverage was also used to determine how influential a case was in determining the regression coefficients.

With high actual influence points explained, interactions developed and transformations included, a final model was tested. This model achieved an R-squared value of 89%. Figure C.5 shows final regression output for the construction speed model. The residual model diagnostics shown in Figure C.6 indicate the model was performing extremely well. The first graph shows the normal plot of residuals. This line should be and is nearly linear. The second chart of residuals in the upper right corner shows time dependency. This test does not apply to this data, therefore, non-independence was not a problem. The histogram in the lower left corner showed a fairly good distribution of residuals, no significant outliers. Finally, testing for constant variance indicated that fitted values were consistent. This was indicated by the random distribution of data points in the graph. The relationship in this graph was severely affected by variables such as unit cost and area. However, transforming these variables allowed the model to track their true relationship to construction speed.

Project area had a positive relationship with construction speed. This made sense because there was plenty to be gained from a large building with repetitive processes. Generally, these types of buildings are simple, exhibit low complexity, include large open spans, require minimal architectural finishes, and generally had experienced teams of designers and builders. However, not always the case, as many high tech fabrication plants were sophisticated, required skilled crafts and excessive attention to quality control. Where these facility types gained in speed was through the relative importance to get them up and running (aggressive schedules) as revenue producing facilities.

As in the first example, the light industrial class (warehouse type facilities) area played an important role in determining construction speed values. In fact, the data was broken into three distinct levels, jobs less than 100,000 square feet, those between 100,000 and 200,000 and those above 200,000 square feet. In each case, construction speed climbed with size.

Finally, in an attempt to clarify measured differences between delivery systems, values for construction speed were calculated using the final model. Values were calculated by developing equations for each possible circumstance by delivery system. This allowed the model to predict values that could then be used for comparison. This was accomplished by allowing the model to calculate unit costs for each job had it been completed using design-build, design-bid-build and then construction management at risk. Developing descriptive statistics on these values allowed for a direct comparison between the performance of each project delivery system.

Main findings show that the construction speed of design-build projects was, on average, at least 12% faster than design-bid-build and 7% faster than construction management at risk. In addition, construction management at risk projects were at least 5.8% faster than design-bid-build.

C.3 DELIVERY SPEED

Delivery speed was similar to construction speed, but included both design and construction durations. It was expected that the delivery speeds achieved on projects using design-build and construction management at risk would be substantially higher due to the potential for activity overlap. In fact, differences between systems were most significant in this performance metric. The technical procedures used to develop the model for delivery speed were very similar to those utilized for construction speed. Sections describing the areas where these models differed are described. Final model results and diagnostics are also offered.

The final best subsets regression is shown in Figure C.7. Initially, area, facility type, the level of architectural finishes, team communication and the experience of team members were explaining 68% of the variation in delivery speed.

In conjunction with the best subsets regression, a model for delivery speed, similar to that used by The University of Reading, was tested. Many of the above variables were similar and showed positive results. Again, this offered a good starting point for the consideration of variables in the best subsets regressions. The opportunity to compare models did not exist for all other response variables because the University of Reading did not report models for cost and schedule growth metrics.

No interaction variables were included in this model. However, residual diagnostics indicated clearly that non-constant variance was an issue. Of the variables being studied, project area was not linear. The proper relationship between facility area and delivery speed was achieved using a log transformation of delivery speed and a weighted log transformation for area. Transforming area greatly improved the residual distribution and the variable's individual significance in the model. In addition, once the proper linear relationship was expressed, levels of explained variation improved dramatically.

Cook's influence distance was used to check for observations exhibiting a high level of actual influence on the models' ability to determine fitted values. Although the values themselves were not extremely large, one job was clearly different from the others. This particular public job suffered from the separation of appropriated funds for design and construction and thus, caused a four year delay between design completion and the start of construction. This job caused the model to inaccurately track the data to its specific situation. Therefore, it was omitted from the model. Leverage was also used to determine how influential a case was in determining the regression coefficients.

With high actual influence points explained and transformations included, a final model was tested. This model achieved an R-squared value of 88%. Figure C.8 shows final regression output for the delivery speed model. The residual model diagnostics shown in Figure C.9 indicate the model performed extremely well. Non-constant variance was corrected through the transformation of area and delivery speed. This allowed the model to track their true relationship.

Main findings showed that the delivery speed of design-build projects was, on average, at least 33.5% faster than design-bid-build and 23.5% faster than construction management at risk. In addition, construction management at risk projects were at least 13.3% faster than design-bid-build.

C.4 COST GROWTH

Cost growth represented the percentage difference between final and contracted project costs. The technical procedures used to develop the model for cost growth were very similar to those utilized for the other models. Sections describing where the models differed are described. Final model results and diagnostics are also offered.

The final best subsets regression is shown in Figure C.10. Initially, the owner's ability to make decisions, the experience of subcontractors with the method of delivery, the presence of legal constraints and specific facility systems were explaining 22% of the variation in cost growth.

No interaction variables were included in this model. Transformations were not used in this model because the relationships between variables were naturally linear. This was made clear by investigating residual diagnostics.

Cook's influence distance was used to check for observations exhibiting a high level of actual influence on the models' ability to determine fitted values. Although the values themselves were not extremely large, three jobs were clearly different from the others. Two were high technology projects, another from the light industrial class. One of the technology projects was a costly renovation, the other, an unusual chemical plant with a unit cost of 674 dollars per square foot. The third constituted an open-air pedestrian walkway atop a seven story parking deck. This project had a peculiar unit cost for its class and was aggressively scheduled due to specific owner characteristics. These three jobs were removed from the model.

With high actual influence points explained and residual diagnostics confirmed, a final model was tested. This model achieved an R-squared value of 24%. Figure C.11 shows final regression output for the cost growth model. The residual model diagnostics shown in Figure C.12 indicate the model was performing adequately. The performance of this model was just over that of the best subsets regression.

Main findings showed that the cost growth of design-build projects was, on average, at least 0.3% less than design-bid-build and 1% less than construction management at risk. In addition, design-bid-build projects were at least 0.5% less than construction management at risk.

C.5 SCHEDULE GROWTH

Schedule growth represented the percentage difference between as planned and as build dates. The technical procedures used to develop the model for schedule growth are very similar to those utilized for the other models. Sections describing where the models differ are described. Final model results and diagnostics are also offered.

The final best subsets regression is shown in Figure C.13. Initially, the owner's ability to make decisions, commercial terms, contract unit cost and project size were explaining 16% of the variation in schedule growth.

No interaction variables were included in this model. Transformations were not used in this model because the relationships between variables were naturally linear. This was made clear by investigating residual diagnostics.

Cook's influence distance was used to check for observations exhibiting a high level of actual influence on the models' ability to determine fitted values. Although the values themselves were not extremely large, four jobs were clearly different from the others. Two of these were light industrial projects, each having extremely high unit cost and schedule growth values. Project three was a complex office facility which had multiple owners and inadequate funding which together, led to untimely decisions, poor communication and severe delays. The fourth project, a multi-story dwelling, experienced schedule growth of 116% percent. Removing these four jobs improved the explained variation by four percent. In addition, residual diagnostics were adjusted.

With high actual influence points explained and residual diagnostics confirmed, a final model was analyzed. This model achieved an R-squared value of 24%. Figure C.14 shows final regression output for the schedule growth model. The residual model diagnostics shown in Figure C.15 indicated the model was performing inadequately. Several observations caused the model to be less than normal. Additionally, the residuals versus fits plot showed a faint regularity of points in a row across the center of the plot. This band was produced by a single group of projects. The data sample included 99 projects with exactly zero percent schedule growth. These jobs finished precisely the date in which they had planned to finish. Therefore, the model had a difficult time estimating or predicting fitted values for zero, thus causing a higher proportion of residual than necessary.

This model showed the schedule growth of design-build projects was, on average, at least 11.4% less than design-bid-build and 2.18% less than construction management at risk. In addition, construction management at risk projects were at least 9.19% less than design-bid-build.

Figure C.1: Final Best Subsets Regression for Unit Cost.

The following variables were included in all models:
Response, fam 1, fam 2, fam 3, fam 4, fam 6, cmr, db

203 cases used 144 cases contain missing values.

```
                                         C       d d N E E E E c
                                         a M   d b b e x x x x o
                                         i a d e / / w O S O S n
                                         s n e s g g   w u w u t
                                         s y s   c c c n b n b u
                                         o L   g     o F F D D n
                R-Sq                     n e l m l g n a a e e i
Vars    R-Sq   (adj)    C-p          S   s g s p s m s c c l l t

   1    99.0    98.9    7.1     19.426                         X
   1    18.5    14.6  2E+04     174.87   X
   2    99.0    99.0    5.1     19.272           X             X
   2    99.0    99.0    6.9     19.365             X           X
   3    99.0    99.0    5.0     19.213   X       X             X
   3    99.0    99.0    6.2     19.271           X         X   X
   4    99.0    99.0    5.9     19.206   X       X         X   X
   4    99.0    99.0    6.3     19.224   X       X           X X
   5    99.0    99.0    7.5     19.232   X       X         X X X
   5    99.0    99.0    7.7     19.242   X       X       X X   X
   6    99.0    99.0    9.3     19.276   X       X     X   X X X
   6    99.0    99.0    9.4     19.279   X       X       X X X X
   7    99.0    99.0   11.3     19.324   X   X   X     X   X X X
   7    99.0    99.0   11.3     19.324   X       X X   X   X X X
   8    99.0    99.0   13.2     19.371   X   X   X X   X   X X X
   8    99.0    99.0   13.2     19.372   X       X X X X   X X X
   9    99.0    98.9   15.1     19.420   X   X   X X X X   X X X
   9    99.0    98.9   15.1     19.421   X   X   X   X X X X X X
  10    99.0    98.9   17.1     19.469   X   X   X X X X X X X X
  10    99.0    98.9   17.1     19.470   X X X   X X X X   X X X
  11    99.0    98.9   19.0     19.520   X X X   X X X X X X X X
  11    99.0    98.9   19.0     19.522   X   X X X X X X X X X X
  12    99.0    98.9   21.0     19.573   X X X X X X X X X X X X
```

Figure C.2: Final Regression Analysis for Unit Cost.

The regression equation is:
LogUnitCost = 0.0664 - 0.0129 fam 1 - 0.0112 fam 2 - 0.0220 fam 3
- 0.0157 fam 4 + 0.0038 fam 5 - 0.0074 1*cmr - 0.0354 2*cmr
+ 0.0037 3*cmr - 0.0068 4*cmr - 0.0135 6*cmr - 0.0142 1*db
- 0.0131 2*db - 0.00537 3*db - 0.0151 4*db - 0.0328 5*db
- 0.0229 6*db + 0.0519 1/LogArea + 0.00215 Response
- 0.0023 caiconfac - 0.0033 caicondel - 0.00350 ManyLeg
+ 0.983 LogContUC

316 cases used 31 cases contain missing values

```
Predictor        Coef        StDev          T        P
Constant      0.06641      0.02185       3.04    0.003
fam 1        -0.01287      0.01107      -1.16    0.246
fam 2        -0.01122      0.01381      -0.81    0.417
fam 3        -0.02202      0.01039      -2.12    0.035
fam 4        -0.01572      0.01285      -1.22    0.222
fam 5         0.00376      0.01788       0.21    0.833
1*cmr        -0.00738      0.01390      -0.53    0.596
2*cmr        -0.03539      0.01925      -1.84    0.067
3*cmr         0.00370      0.01119       0.33    0.741
4*cmr        -0.00680      0.01244      -0.55    0.585
6*cmr        -0.01349      0.01113      -1.21    0.226
1*db        -0.014191     0.008679      -1.64    0.103
2*db         -0.01306      0.01621      -0.81    0.421
3*db        -0.005370     0.009379      -0.57    0.567
4*db         -0.01505      0.01267      -1.19    0.236
5*db         -0.03284      0.01956      -1.68    0.094
6*db         -0.02291      0.01238      -1.85    0.065
1/LogAre      0.05186      0.09327       0.56    0.579
Response     0.002152     0.005893       0.37    0.715
caiconfa     -0.00228      0.02889      -0.08    0.937
caiconde     -0.00327      0.02661      -0.12    0.902
ManyLeg     -0.003502     0.004419      -0.79    0.429
LogContU     0.983296     0.007990     123.06    0.000

S = 0.03499     R-Sq = 99.1%     R-Sq(adj) = 99.0%

Analysis of Variance

Source       DF          SS          MS         F         P
Regression   22     38.0218      1.7283   1411.47     0.000
Error       293      0.3588      0.0012
Total       315     38.3805
```

Figure C.3: Residual Model Diagnostics for Unit Cost.

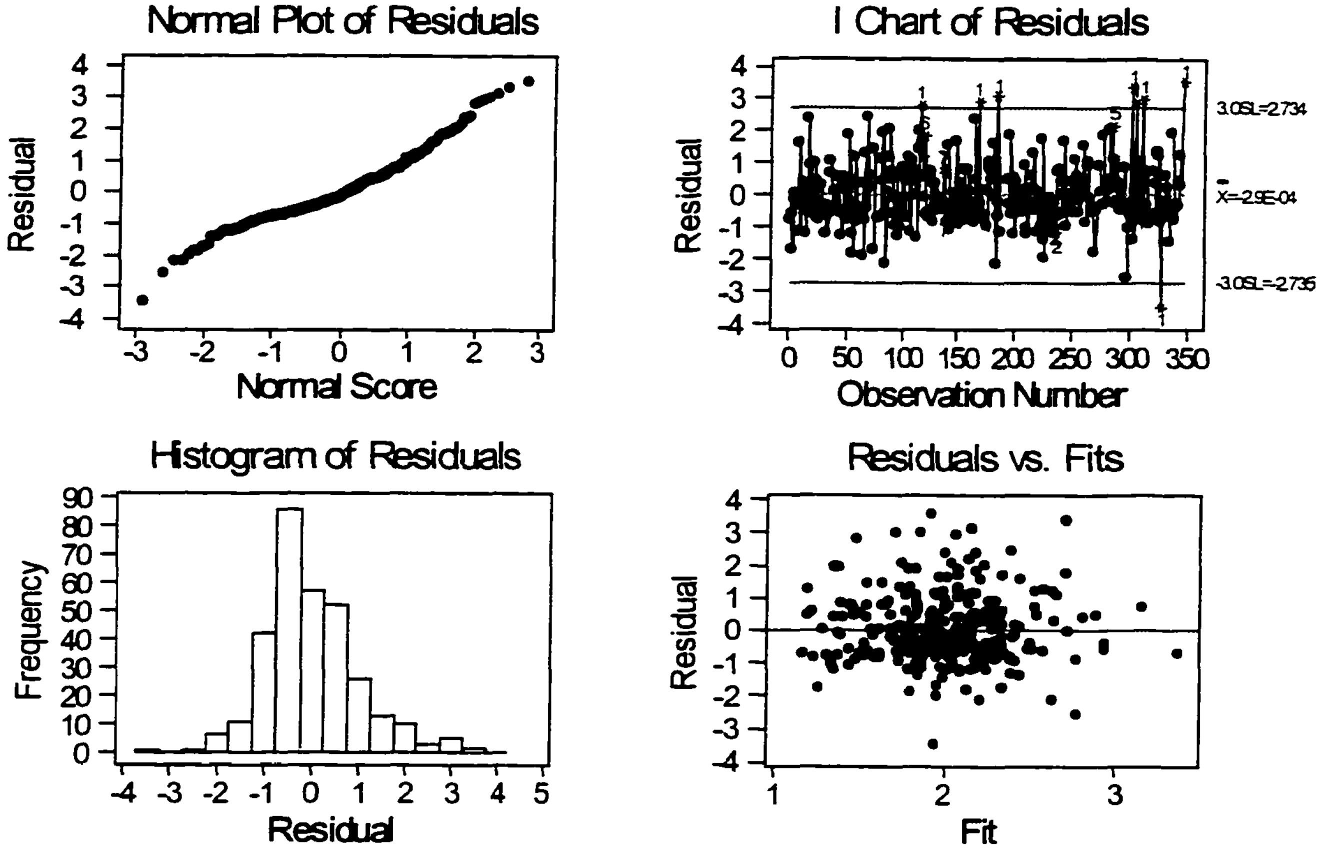


Figure C.4: Final Best Subsets Regression for Construction Speed.

The following variables were included in all models:
Response, fam 1, fam 2, fam 3, fam 4, fam 6, cmr, db

329 cases used 20 cases contain missing values.

```
                                   N E D N C           R     1
                                   u x e e o       A   e     /
                                   m S s w n     E v   s     l
                                   C u C   t f f x g H p     o
                                   l b m c u a a C C C o     g
                                   a F p o n m m o p p n c   w
            R-Sq                   u a l n i     m l l s m d e
Vars  R-Sq  (adj)    C-p        S  s c t s t 5 l m x x e r b i

   1  55.2   55.0   87.6    11121                            X
   1  16.1   15.9  447.2    15213              X
   2  61.3   61.1   33.3    10349              X             X
   2  58.0   57.7   63.8    10783                          X X
   3  62.7   62.3   22.7    10180    X         X             X
   3  62.6   62.3   22.9    10183              X           X X
   4  64.2   63.8   10.5   9983.6    X         X           X X
   4  64.1   63.7   11.3   9996.2    X X       X             X
   5  64.7   64.1    8.4   9936.3    X X       X           X X
   5  64.5   64.0    9.5   9953.3    X X     X X             X
   6  64.9   64.3    7.8   9911.3    X X     X X           X X
   6  64.9   64.2    8.3   9919.8    X         X   X X     X X
   7  65.4   64.6    5.8   9865.3    X X       X   X X     X X
   7  65.3   64.5    6.6   9878.0    X X     X X   X X       X
   8  65.7   64.9    4.6   9831.3    X X     X X   X X     X X
   8  65.5   64.7    6.4   9859.7    X X       X   X X X   X X
   9  65.8   64.9    5.4   9827.9    X X     X X   X X X   X X
   9  65.7   64.8    6.4   9842.9    X X     X X X X X     X X
  10  65.9   64.8    7.2   9839.6    X X     X X X X X X   X X
  10  65.9   64.8    7.3   9841.8    X X X   X X   X X X   X X
  11  65.9   64.7    9.1   9853.9    X X X   X X X X X X   X X
  11  65.9   64.7    9.1   9854.3    X X     X X X X X X X X X
  12  65.9   64.6   11.0   9868.7    X X X   X X X X X X X X X
  12  65.9   64.6   11.1   9869.1  X X X X   X X X X X X   X X
  13  65.9   64.5   13.0   9884.1  X X X X   X X X X X X X X X
  13  65.9   64.5   13.0   9884.1    X X X X X X X X X X X X X
  14  65.9   64.4   15.0   9899.7  X X X X X X X X X X X X X X
```

Figure C.5: Final Regression Analysis for Construction Speed

The regression equation is:
logCspd = - 1.32 + 0.0553 fam 1 + 0.0674 fam 2 + 0.0829 fam 3 - 0.0424 fam 4
+ 0.189 fam 5 + 0.210 1*cmr - 0.0017 2*cmr + 0.0201 3*cmr
+ 0.113 4*cmr + 0.0720 6*cmr + 0.0941 1*db - 0.0652 2*db
+ 0.0476 3*db + 0.205 4*db - 0.0444 5*db + 0.121 6*db
- 0.0359 HCplx + 0.0430 Response + 0.0930 ExComm + 1.12 1/logUC
+ 0.0742 DesCmplt - 25.9 1/logweightarea

344 cases used 5 cases contain missing values

```
Predictor        Coef       StDev          T        P
Constant      -1.3227      0.1199     -11.03    0.000
fam 1         0.05528     0.05501       1.00    0.316
fam 2         0.06738     0.06783       0.99    0.321
fam 3         0.08286     0.05382       1.54    0.125
fam 4        -0.04238     0.06421      -0.66    0.510
fam 5         0.18863     0.09218       2.05    0.042
1*cmr         0.21048     0.07307       2.88    0.004
2*cmr        -0.00172     0.09947      -0.02    0.986
3*cmr         0.02013     0.05684       0.35    0.723
4*cmr         0.11333     0.06259       1.81    0.071
6*cmr         0.07201     0.05550       1.30    0.195
1*db          0.09411     0.04755       1.98    0.049
2*db         -0.06522     0.08036      -0.81    0.418
3*db          0.04764     0.05000       0.95    0.341
4*db          0.20470     0.06757       3.03    0.003
5*db         -0.04438     0.09950      -0.45    0.656
6*db          0.12108     0.06209       1.95    0.052
HCplx        -0.03593     0.02301      -1.56    0.119
Response      0.04302     0.02933       1.47    0.143
ExComm        0.09304     0.02403       3.87    0.000
1/logUC        1.1153      0.1234       9.04    0.000
DesCmplt      0.07418     0.02605       2.85    0.005
1/logwei     -25.9248      0.7063     -36.70    0.000

S = 0.1827       R-Sq = 88.9%     R-Sq(adj) = 88.1%

Analysis of Variance

Source       DF          SS          MS         F        P
Regression   22     85.8227      3.9010    116.91    0.000
Error       321     10.7107      0.0334
Total       343     96.5334
```

Figure C.6: Residual Model Diagnostics for Construction Speed.

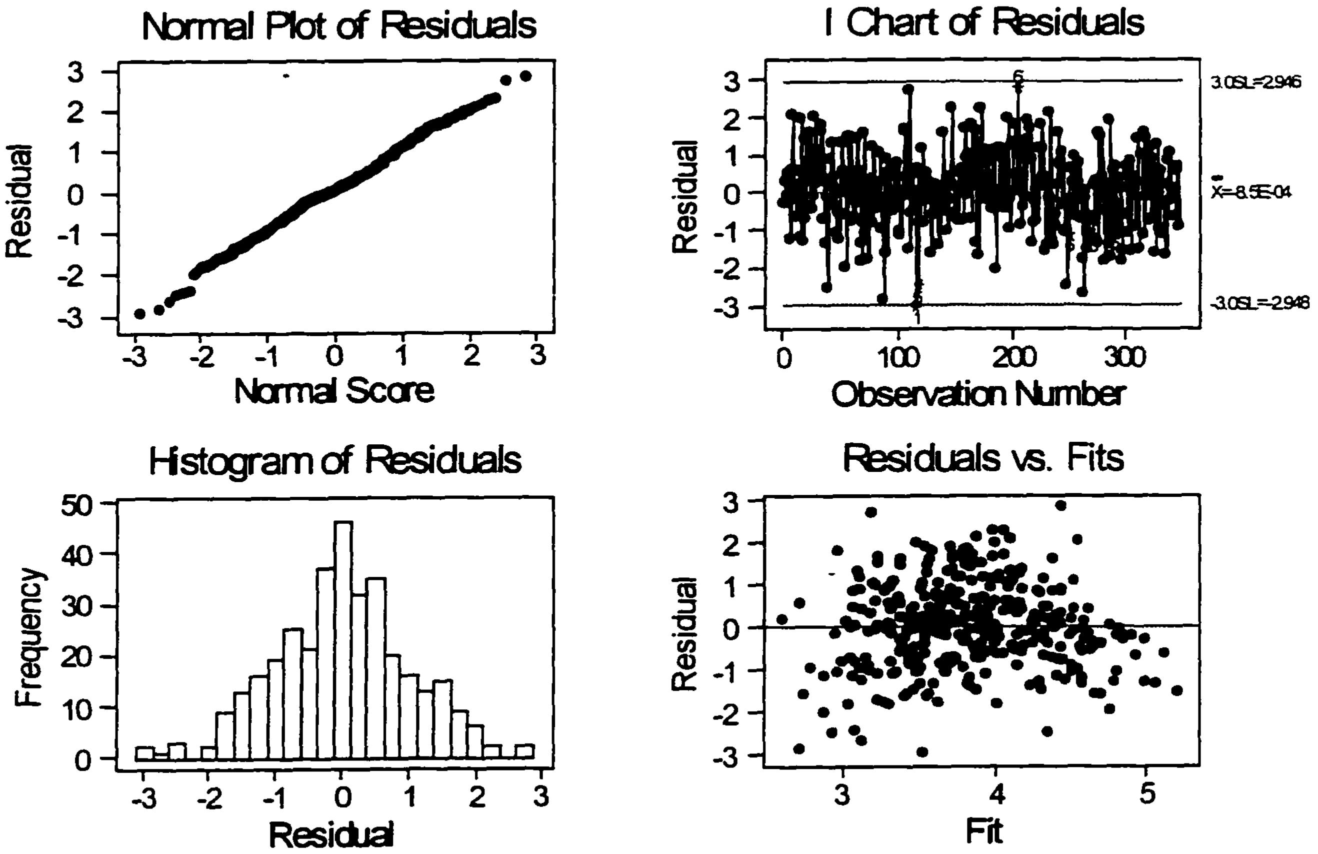


Figure C.7: Final Best Subsets Regression for Delivery Speed.

The following variables were included in all models:
Response, fam 1, fam 2, fam 3, fam 4, fam 6, cmr, db

304 cases used 46 cases contain missing values.

```
                                         N P   E D N C
                                         u o   x e e o     A
                                         m o E S s w n E   v
                                         C r x u C   t x H g
                                         l O C b m c U C C C A
                                       M a C h F p o n o p p r
               R-Sq                    i u a e a l n i m l l e
Vars   R-Sq   (adj)   C-p           S  n s p m c t s t m x x a

   1   63.5    62.4   39.8     8369.3                        X
   1   25.6    23.3  376.3      11951                X
   2   64.7    63.5   30.8     8239.6  X                     X
   2   64.4    63.2   34.1     8283.2          X             X
   3   65.5    64.2   26.2     8166.0  X       X             X
   3   65.5    64.2   26.3     8167.7          X X           X
   4   66.4    65.0   20.5     8076.0  X       X X           X
   4   66.1    64.7   22.8     8107.1  X       X       X     X
   5   66.8    65.4   18.2     8031.7  X       X X   X       X
   5   66.8    65.3   18.3     8032.7  X       X X     X     X
   6   67.3    65.7   16.2     7990.4  X       X X   X X     X
   6   67.2    65.6   17.4     8007.5  X   X   X X     X     X
   7   67.6    65.9   15.3     7964.6  X   X   X X   X X     X
   7   67.4    65.7   16.9     7987.0  X       X X     X X X X
   8   67.9    66.1   15.2     7949.7  X       X X   X X X X X
   8   67.7    65.9   16.4     7965.4  X   X   X X   X X X   X
   9   68.1    66.2   15.4     7937.5  X   X   X X   X X X X X
   9   67.9    66.0   17.1     7961.5  X     X X X   X X X X X
  10   68.1    66.1   17.2     7948.7  X   X X X X   X X X X X
  10   68.1    66.1   17.2     7949.3  X X X   X X   X X X X X
  11   68.1    66.0   19.0     7960.7  X X X X X X   X X X X X
  11   68.1    66.0   19.1     7962.1  X   X X X X X X X X X X
  12   68.1    65.9   21.0     7974.3  X X X X X X X X X X X X
```

Figure C.8: Final Regression Analysis for Delivery Speed.

The regression equation is:
logdelspd = - 1.12 + 0.0864 fam 1 - 0.0734 fam 2 - 0.0751 fam 3 - 0.130 fam 4
+ 0.220 fam 5 + 0.198 1*cmr + 0.062 2*cmr + 0.0985 3*cmr
+ 0.130 4*cmr - 0.0265 6*cmr + 0.206 1*db + 0.132 2*db + 0.239 3*db
+ 0.297 4*db - 0.019 5*db + 0.138 6*db - 0.101 NumClaus
+ 0.0673 ExSubFac + 0.101 DesCmplt -0.000257 ContUnitCost
+ 0.128 ExComm - 0.208 HCplx - 0.154 AvgCplx - 0.0195 Response
- 0.0757 New const - 28.3 1/logareaweight

328 cases used 22 cases contain missing values

```
Predictor        Coef         StDev          T        P
Constant      -1.1231        0.1554      -7.23    0.000
fam 1         0.08643       0.06537       1.32    0.187
fam 2        -0.07338       0.08260      -0.89    0.375
fam 3        -0.07514       0.06427      -1.17    0.243
fam 4        -0.12983       0.08283      -1.57    0.118
fam 5          0.2198        0.1071       2.05    0.041
1*cmr         0.19769       0.08698       2.27    0.024
2*cmr          0.0621        0.1158       0.54    0.592
3*cmr         0.09850       0.06568       1.50    0.135
4*cmr         0.13042       0.07923       1.65    0.101
6*cmr        -0.02647       0.06601      -0.40    0.689
1*db          0.20588       0.05662       3.64    0.000
2*db          0.13228       0.09520       1.39    0.166
3*db          0.23909       0.05845       4.09    0.000
4*db          0.29692       0.08377       3.54    0.000
5*db          -0.0195        0.1144      -0.17    0.865
6*db          0.13837       0.07315       1.89    0.060
NumClaus     -0.10053       0.04105      -2.45    0.015
ExSubFac      0.06725       0.02591       2.60    0.010
DesCmplt      0.10093       0.03061       3.30    0.001
ContUnit -0.00025657    0.00006042      -4.25    0.000
ExComm        0.12840       0.02856       4.49    0.000
HCplx        -0.20803       0.05592      -3.72    0.000
AvgCplx      -0.15450       0.05377      -2.87    0.004
Response     -0.01948       0.03454      -0.56    0.573
New cons     -0.07568       0.02986      -2.53    0.012
1/logare     -28.2668        0.8449     -33.46    0.000

S = 0.2094      R-Sq = 87.5%      R-Sq(adj) = 86.4%

Analysis of Variance

Source       DF        SS          MS         F        P
Regression   26     92.5892     3.5611     81.19    0.000
Error       301     13.2024     0.0439
Total       327    105.7917
```

Figure C.9: Residual Model Diagnostics for Delivery Speed.

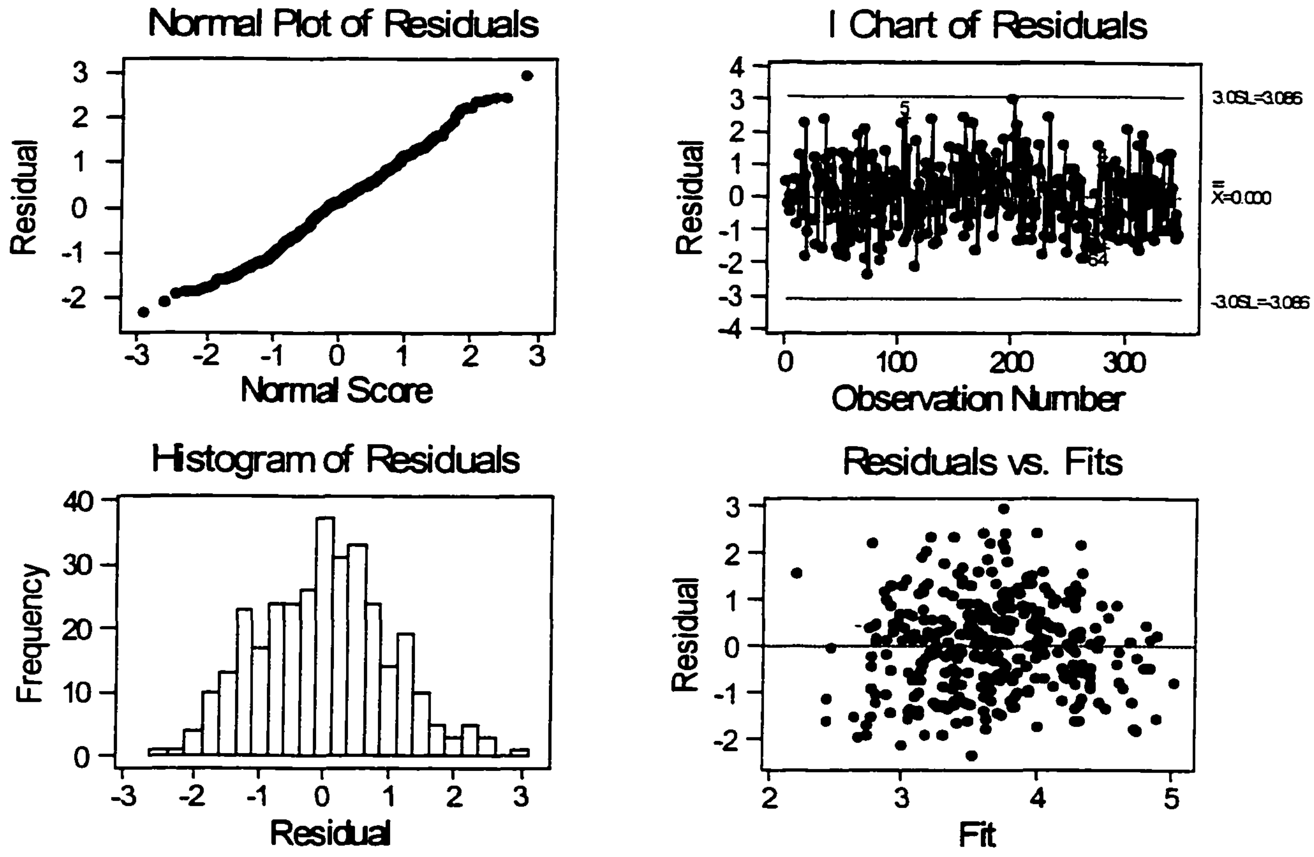


Figure C.10: Final Best Subsets Regression for Cost Growth.

The following variables were included in all models:
Response, fam 1, fam 2, fam 3, fam 4, fam 6, cmr, db

196 cases used 152 cases contain missing values.

```
                                            d d N E E E     P E E     N C     C
                                          d b b e x x x     o x x   M u a     o
                                          e / / w O C S E   o S D   a m i     n
                                          s g g   w o u x   r u e H n C s     t
                                            c c c n n b C   S b c C y l s     U
                                          g     o F F F h P c D i p L a o M n
                R-Sq                      m c g n a a a e u o e d l e u n a i
Vars    R-Sq   (adj)     C-p         S    p p m s c c c m b p l e x g s s t t

   1     6.9      2.4    30.2    8.0298   X
   1     6.7      2.2    30.5    8.0366         X
   2     9.8      4.9    25.7    7.9247   X     X
   2     9.5      4.7    26.3    7.9354         X                           X
   3    12.6      7.4    21.5    7.8209   X     X                     X
   3    12.3      7.1    22.1    7.8334   X     X                           X
   4    15.0      9.4    18.2    7.7342   X     X                     X     X
   4    14.7      9.2    18.8    7.7458   X     X                     X X
   5    16.3     10.3    17.3    7.6947   X     X               X     X X
   5    16.2     10.2    17.6    7.7020   X     X       X             X     X
   6    17.5     11.2    16.6    7.6595   X     X       X         X   X X
   6    17.4     11.0    16.9    7.6662   X     X               X X   X X
   7    18.7     12.0    15.9    7.6251   X X   X       X         X   X X
   7    18.6     11.8    16.3    7.6322   X     X       X         X   X X   X
   8    19.6     12.4    16.0    7.6062   X     X       X     X   X   X X   X
   8    19.5     12.3    16.2    7.6089   X X   X       X         X   X X   X
   9    20.2     12.6    16.7    7.5984   X X X X       X         X   X X   X
   9    20.2     12.6    16.7    7.5986   X     X       X     X X X   X X   X
  10    20.9     12.8    17.2    7.5875   X X X X       X     X   X   X X   X
  10    20.7     12.7    17.5    7.5944   X     X X X X X         X   X X   X
  11    21.4     12.9    18.0    7.5839   X X X X       X     X X X   X X   X
  11    21.4     12.9    18.1    7.5858   X X   X X X X X         X   X X   X
  12    21.9     12.9    19.0    7.5827   X X X X       X     X X X   X X X X
  12    21.9     12.9    19.0    7.5835   X X X X X X X X         X   X X   X
  13    22.3     12.9    20.1    7.5845   X X X X       X     X X X X X X X X
  13    22.2     12.9    20.1    7.5859   X X X X X X X X         X X X X   X
```

Figure C.11: Final Regression Analysis for Cost Growth.

The regression equation is:
CostGrwth = 10.6 + 0.22 fam 1 - 1.79 fam 2 - 2.16 fam 3 - 1.88 fam 4
+ 0.03 fam 5 + 0.16 1*cmr - 3.49 2*cmr + 3.59 3*cmr + 2.23 4*cmr
+ 0.71 6*cmr + 1.44 1*db - 1.59 2*db - 3.87 3*db - 1.54 4*db
+ 7.07 5*db - 1.23 6*db + 8.67 des gmp - 3.72 db/gc cp
- 2.57 db/gc gmp - 3.57 New const + 0.74 ExSubFac - 2.78 ExChem
+ 2.23 HCplx - 1.42 ManyLeg + 3.78 NumClaus - 4.62 Caissons
+ 0.08 Response - 0.00276 ContUnitCost

196 cases used 152 cases contain missing values

```
Predictor          Coef         StDev            T          P
Constant         10.600         2.665         3.98      0.000
fam 1             0.221         2.543         0.09      0.931
fam 2            -1.788         3.162        -0.57      0.572
fam 3            -2.158         2.577        -0.84      0.404
fam 4            -1.884         3.252        -0.58      0.563
fam 5             0.027         4.314         0.01      0.995
1*cmr             0.164         3.191         0.05      0.959
2*cmr            -3.491         4.337        -0.80      0.422
3*cmr             3.588         2.706         1.33      0.187
4*cmr             2.231         3.081         0.72      0.470
6*cmr             0.709         2.679         0.26      0.792
1*db              1.438         3.093         0.46      0.643
2*db             -1.590         7.901        -0.20      0.841
3*db             -3.867         3.820        -1.01      0.313
4*db             -1.541         4.130        -0.37      0.709
5*db              7.073         5.816         1.22      0.226
6*db             -1.227         3.893        -0.32      0.753
des gmp           8.667         2.776         3.12      0.002
db/gc cp         -3.718         1.843        -2.02      0.045
db/gc gm         -2.567         1.588        -1.62      0.108
New cons         -3.575         1.303        -2.74      0.007
ExSubFac          0.745         1.239         0.60      0.549
ExChem           -2.775         1.192        -2.33      0.021
HCplx             2.230         1.289         1.73      0.086
ManyLeg          -1.422         1.352        -1.05      0.294
NumClaus          3.776         1.935         1.95      0.053
Caissons         -4.617         2.692        -1.71      0.088
Response          0.078         1.888         0.04      0.967
ContUnit      -0.002763      0.002516        -1.10      0.274

S = 7.322         R-Sq = 24.4%       R-Sq(adj) = 11.7%

Analysis of Variance

Source        DF          SS           MS          F         P
Regression    28     2891.19       103.26       1.93     0.006
Error        167     8954.25        53.62
Total        195    11845.44
```

Figure C.12: Residual Model Diagnostics for Cost Growth.

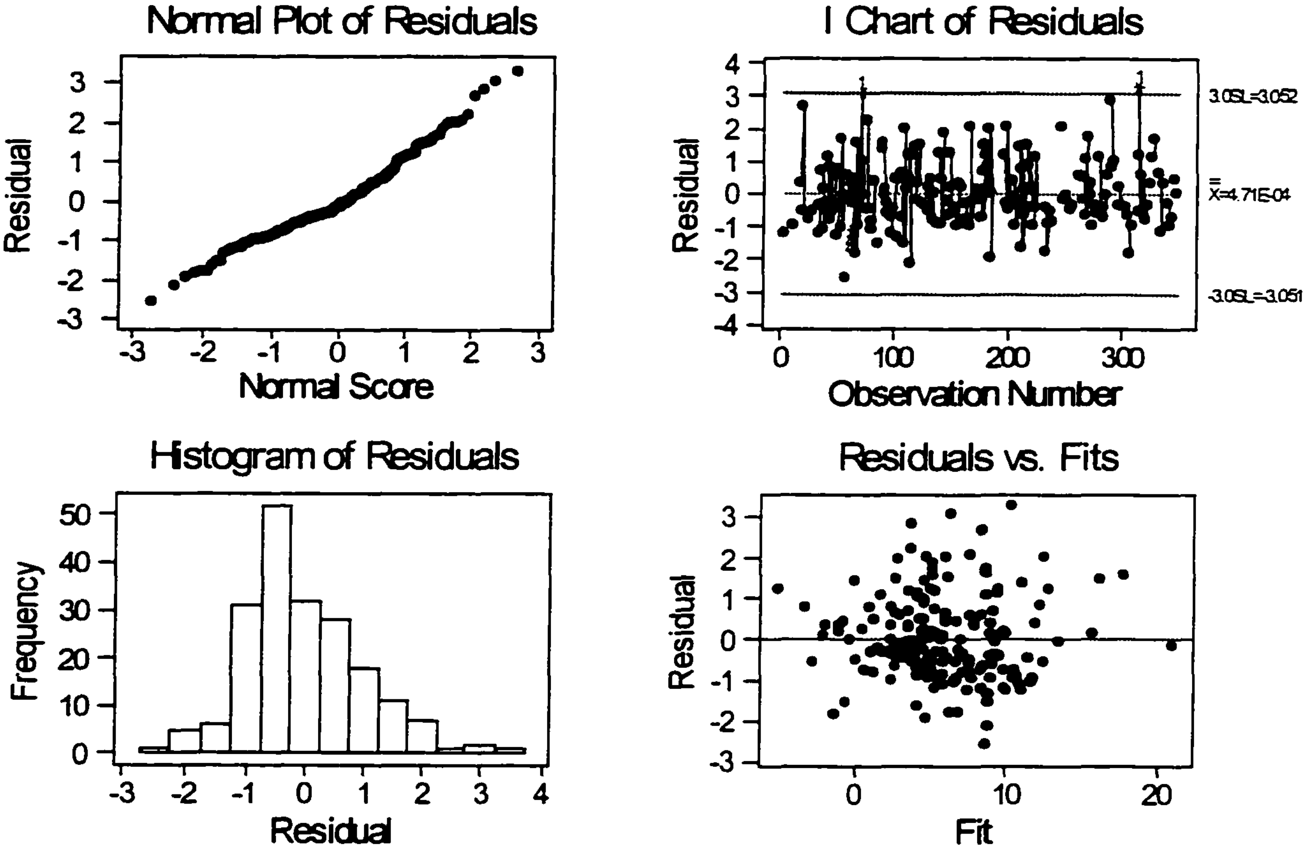


Figure C.13: Final Best Subsets Regression for Schedule Growth.

The following variables were included in all models:
Response, fam 1, fam 2, fam 3, fam 4, fam 6, cmr, db.

202 cases used 145 cases contain missing values.

```
                                      c   P E A     E       N
                                      o   o x d   E x   E   e   Y
                                      n   o D q   x C E x d w   e
                                      u   r e D   D o x S e   n s
                                      n A S c e   B n C c s c e P
                                      i r c i c C D D o o   o g o
              R-Sq                    t e o d i I e e m p l n o o
Vars   R-Sq  (adj)   C-p         S   c a p e d P l l m e s s t l

   1   13.0    8.9    5.3    12.442     X
   1   10.6    6.4   10.4    12.608                         X
   2   14.2    9.7    4.7    12.387   X X
   2   13.6    9.1    5.9    12.427     X                 X
   3   15.1   10.2    4.7    12.352   X X                 X
   3   14.6    9.6    5.9    12.392   X X   X
   4   15.5   10.1    5.9    12.358   X X   X             X
   4   15.4   10.0    6.1    12.363   X X       X         X
   5   15.9   10.1    7.0    12.360   X X   X   X         X
   5   15.7    9.9    7.4    12.374   X X   X           X X
   6   16.2    9.9    8.5    12.374   X X   X   X X       X
   6   16.1    9.8    8.5    12.376   X X   X   X       X X
   7   16.4    9.6    9.9    12.389   X X   X   X X     X X
   7   16.4    9.6   10.0    12.391   X X   X   X X       X     X
   8   16.6    9.4   11.4    12.405   X X   X   X X     X X     X
   8   16.5    9.3   11.7    12.415   X X   X   X X     X X X
   9   16.7    9.1   13.2    12.430   X X X X   X X     X X     X
   9   16.7    9.0   13.2    12.431   X X   X X X X     X X     X
  10   16.8    8.6   15.1    12.460   X X X X   X X     X X X   X
  10   16.8    8.6   15.1    12.462   X X   X X X X     X X X   X
  11   16.8    8.1   17.0    12.493   X X X X X X X     X X X   X
  11   16.8    8.1   17.0    12.493   X X X X   X X     X X X X X
  12   16.8    7.6   19.0    12.527   X X X X X X X     X X X X X
  12   16.8    7.6   19.0    12.527   X X X X X X X X   X X X   X
  13   16.8    7.1   21.0    12.561   X X X X X X X X   X X X X X
  13   16.8    7.1   21.0    12.561   X X X X X X X   X X X X X X
  14   16.8    6.6   23.0    12.596   X X X X X X X X X X X X X X
```

Figure C.14: Final Regression Analysis for Schedule Growth.

The regression equation is:
SchedGrwth = 15.3 - 4.05 fam 1 + 6.72 fam 2 + 1.69 fam 3 + 9.11 fam 4
- 10.0 fam 5 - 5.02 1cmr - 4.95 2cmr - 8.69 3cmr - 16.3 4cmr
- 7.69 6cmr - 0.73 1db - 18.8 2db - 9.01 3db - 25.9 4db - 1.08 5db
- 7.83 6db - 3.46 Response - 0.00560 planS - 0.04 New const
- 1.05 negot + 4.07 YesPool - 6.12 ExSubFac - 2.88 des ls

215 cases used 132 cases contain missing values

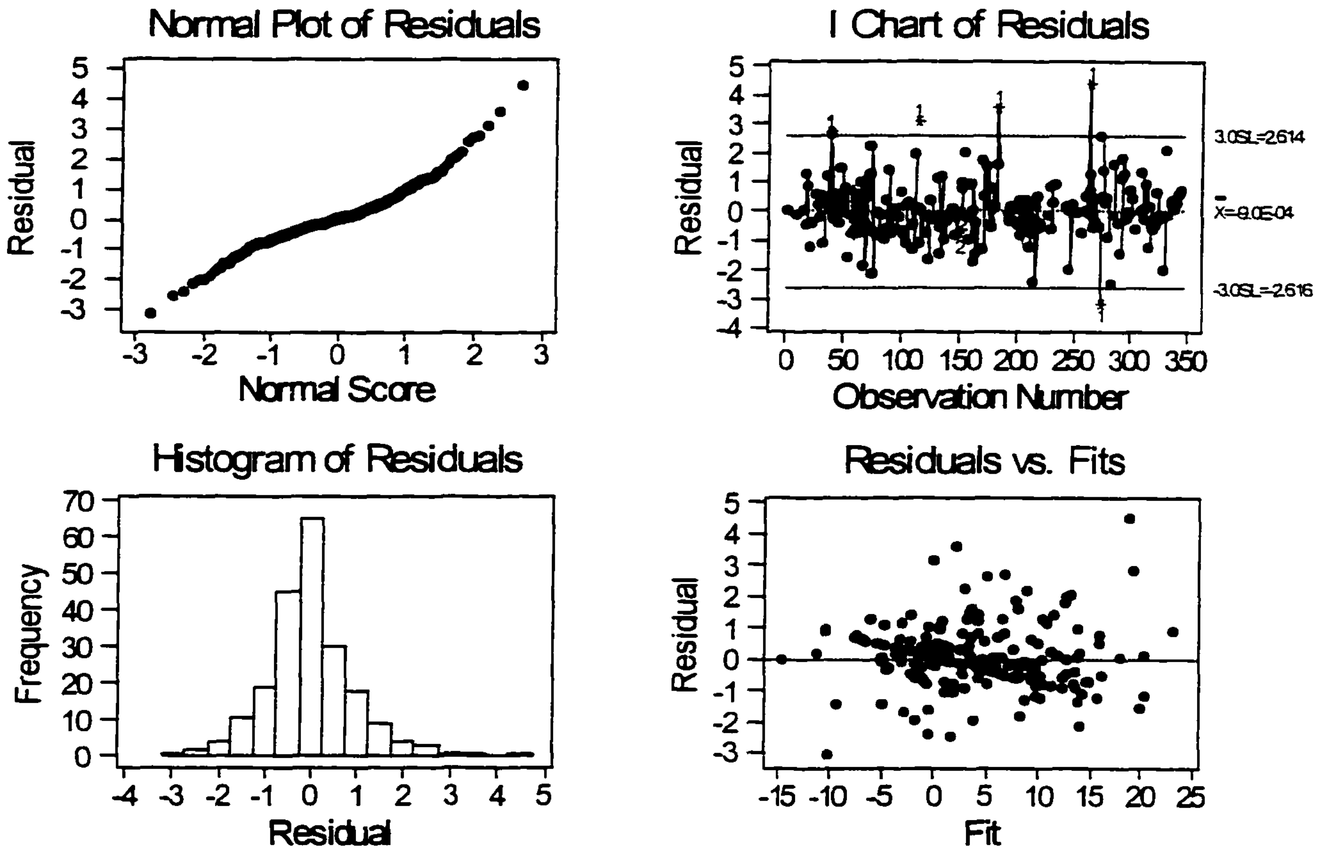
```
Predictor        Coef        StDev          T        P
Constant       15.254        4.800       3.18    0.002
fam 1          -4.047        3.874      -1.04    0.298
fam 2           6.722        4.937       1.36    0.175
fam 3           1.689        3.740       0.45    0.652
fam 4           9.110        4.683       1.95    0.053
fam 5         -10.028        7.257      -1.38    0.169
1cmr           -5.018        5.186      -0.97    0.334
2cmr           -4.951        7.876      -0.63    0.530
3cmr           -8.688        4.364      -1.99    0.048
4cmr          -16.315        4.765      -3.42    0.001
6cmr           -7.686        4.058      -1.89    0.060
1db            -0.733        5.913      -0.12    0.901
2db            -18.81        13.85      -1.36    0.176
3db            -9.008        6.694      -1.35    0.180
4db           -25.943        7.038      -3.69    0.000
5db            -1.075        9.360      -0.11    0.909
6db            -7.827        6.705      -1.17    0.245
Response       -3.463        2.806      -1.23    0.219
planS       -0.005599     0.001778      -3.15    0.002
New cons       -0.036        2.165      -0.02    0.987
negot          -1.054        2.363      -0.45    0.656
YesPool         4.069        3.006       1.35    0.177
ExSubFac       -6.121        2.095      -2.92    0.004
des ls         -2.881        2.086      -1.38    0.169

S = 12.97       R-Sq = 23.6%     R-Sq(adj) = 14.4%

Analysis of Variance

Source        DF          SS          MS         F         P
Regression    23      9903.9       430.6      2.56     0.000
Error        191     32116.9       168.2
Total        214     42020.8
```

Figure C.15: Residual Model Diagnostics for Schedule Growth.



VITA

Mark D. Konchar graduated from The Pennsylvania State University in 1994 with a Bachelor of Architectural Engineering. Prior to and during graduate school, Mark worked with several different companies. As an engineering intern at Arco Chemical Company, he worked extensively in both process and project optimization groups at the Beaver Valley Plant, Pittsburgh, PA. Mark worked as a field engineer on a surveying crew with Widmer Consultants, of Pittsburgh, PA on several Pennsylvania roadway projects. Mark also held two positions with Hensel Phelps Construction Co. As an office engineer, he worked on the $95 million dollar design-build partnership for the New Elitch Gardens. As a field engineer, he coordinated engineers and craftsmen on building layout and line and grade surveying, on fifteen vehicle emissions testing facilities, both in downtown Denver, CO.

During graduate school, Mark worked at the National Association of Home Builders Research Center in Upper Marlboro, Maryland. There he worked as a research intern in the international and military housing division supporting the development of a building technology information center in Russia. He was also responsible for a $1 million contract with the Consumers' Power Safety Commission to develop a guide series for upgrading deteriorated residential electrical wiring systems.

Mark worked with The Haskell Company in Jacksonville, Florida to investigate company specific, design-build best practices. He worked jointly with management to design and document a series for critical in-house company procedures such as strategic planning and responding to competitive design-build RFQ and RFP requests. Portions of this work were later published by the Design-Build Institute of America. Mark also worked as an assistant project manager on a $40 million design-build proposal to the United States Postal Service for a 300,000 square foot information/accounting service center.

While at Penn State, Mark lectured and advised students in undergraduate thesis courses. He was also an instructor at an industry shortcourse on design-build best practice in Pittsburgh, PA. Mark has also participated in the development of the Partnership for achieving Construction Excellence (PACE). He was the chairman of the 1996 and 1997 Roundtable and Research Seminars.