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Correlation between Construction Intensity and the Level of Integration within Design-Bid-Build, Design-Build, and Design-Build-Operate Project Delivery Methods in Water/Wastewater Facility Projects

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CORRELATION BETWEEN CONSTRUCTION INTENSITY AND THE LEVEL OF INTEGRATION WITHIN DESIGN-BID-BUILD, DESIGN-BUILD, AND DESIGN-BUILD-OPERATE PROJECT DELIVERY METHODS IN WATER/WASTEWATER FACILITY PROJECTS

By

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ABSTRACT

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Correlation between Construction Intensity and the Level of Integration within Design-Bid-Build, Design-Build, and Design-Build-Operate Project Delivery Methods in Water/Wastewater Facility Projects

Thesis directed by Department and K. Stanton Lewis Chair, Professor Keith R. Molenaar

This research compares the Design-Bid-Build (DBB), Design-Build (DB), and Design-Build-Operate (DBO) project delivery methods (PDMs) using the construction intensity (CI) project performance metric. Specifically, the comparison relates the degree to which each PDM is "integrated" to its ability to deliver water/wastewater projects at a certain level of CI. The level of integration is defined by previous research and related to the degree in which the producing parties are combined during the phases of design, construction, and operations & maintenance. The results indicate that an increased level of integration has a positive correlation to a greater degree of CI. A discussion of the results is presented along with a viable application for industry owners regarding the use of CI as a new factor, among other pre-existing factors, to be used to make better decisions during the procurement process, leading to the selection of the most appropriate PDM for individual projects.

DEDICATION

I would like to dedicate this Master's Thesis to my mother, Alma Navarro. I cannot express to you how grateful I am to you for pushing me and supporting me in everything I do. You are my inspiration and an amazing mother. I love you.

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First and foremost, I would like to thank my Lord and Savior for carrying me through one of the most challenging years I have faced thus far. I look forward to facing even greater challenges and witnessing your strength pass through me in our accomplishments together.

"I can do all things through Christ who strengthens me."

Philippians 4:13

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CHAPTER I

INTRODUCTION

Purpose of the Research

The purpose of this research was to determine if a correlation exists between the project performance metric Construction Intensity (CI) and the degree of integration within a Project Delivery Method (PDM) for project delivered in the water/wastewater sector. Formal and rigorous statistical analyses were used to define and measure this correlation. Specifically, the analyses were limited to the Design-Bid-Build (DBB), Design-Build (DB), and Design-Build-Operate (DBO) PDMs utilized within the United States (US). A prior research study conducted by Bogus, Shane, and Molenaar in 2008 determined a relationship among DBB and DB water/wastewater projects and CI; however, the study did not encompass more integrated PDMs in the analysis. This research expands on the findings of Bogus et. al. (2008) to deduce the relationship between both segmented and integrated PDMs and the CI project performance metric by adding DBO projects to the comparison.

The findings of this research contribute to the existing literature surrounding cost and schedule project performance metrics as well as the literature regarding the DBB, DB and DBO PDMs. Furthermore, the findings here may be advantageously applied in the industry and used by owners in the procurement decision-making process to help contribute to making more informed decisions. Owners looking to make the critical decision as to what would be the *most appropriate* PDM for delivering an individual water/wastewater project now have more cost and schedule data related to PDMs to use and help guide this determination.

Research Objectives

The overarching objectives of this investigation were to: 1) determine if a correlation exists between CI and the level of integration inherent in the DBB, DB, and DBO PDMs for water/wastewater projects; and 2) apply the findings to the construction industry. The objectives serve as the overall vision for the research. In accomplishing these objectives, specific research goals were developed to dictate milestone achievements or data collection efforts, guiding the achievement of the vision. The specific research goals were to: 1) collect a minimum of 30 water/wastewater infrastructure projects, either current or past, for each of the three PDMs; 2) collect design and construction (D&C) duration and hard cost data for each project data point; 3) determine the level of integration for the DBB, DB, and DBO PDMs; and 4) classify these levels of integration utilizing the Miller et. al. (2000) delivery integration continuum. All the research goals and the research objectives were achieved.

Scope of the Research

The scope of this research involved the collection and creation of a variety of research elements to build a successful research result. It began with a survey of the existing literature regarding the water/wastewater sector, segmented and integrated PDMs, CI, and research methods to develop a research context, need, methodology and point of departure. After establishing the background and context, the overarching objectives and specific research goals were developed. Subsequently, a determination of the project-level information necessary to answer the research question was prescribed to be the project name, location, scope of work, PDM used, and D&C capital costs and duration.

The development of a data collection instrument and listing of potential projects followed this decision. From this list of projects, potential research participants were identified on the basis of their proximity to the project and knowledge of the industry. For this research, project managers, engineers, and utility owners were determined to fulfill this basis and were individually contacted by way of telephone or email to facilitate the data collection process.

The collected data was then stored in a Microsoft Excel database for sorting and cleaning. Subsequently, the data was analyzed under three separate scenarios using a formal and widely accepted statistical comparison method. The results of the analyses were used to make inferences about the water/wastewater research populations. A discussion of a viable industry application based on these inferences follows the presentation of the results. Overall, the scope of this research study follows the framework for a formal research approach.

Data Analysis

A brief literature review of data analysis methods determined that an Analysis of Variance (ANOVA) was the most appropriate statistical comparison method for this research. An ANOVA is, most simplistically, an extension of the two-sample t-test and simultaneously compares the means *between* samples to the mean *within* a sample to determine if the averages across all samples are equal. However, because the three sample sets compared were comprised of a differing number of data points in addition to displaying non-normal behavior, a traditional Fischer ANOVA could not be employed. Instead, a Brown-Forsyth ANOVA (or Levene's improved test) was applied to compare the spread (variance) between the samples, and a Welch ANOVA test was used to compare the location (central tendency) between the samples. Both tests are robust to non-normal behavior and unequal sample sizes, and therefore, provide the most accurate results.

The analysis in Chapter IV of this research is an analysis on a cleaned data set, or a data set in which lower and upper outliers were removed using both a quantitative and qualitative method. Moreover, two additional analyses—one where all data points collected are considered and another where only projects exhibiting a D&C capital cost over five million USD but less than 50 million USD are considered—were also completed. The full procedures for both are included in Appendices B and C. Considering all data points in the analysis caters to the view that all construction projects are unique, and therefore, all should be considered in the analysis to yield a comprehensive view of what is occurring in the underlying research populations. In contrast, considering only those projects in the five million to 50 million USD category places a constraint on the D&C capital costs and their ability to affect the CI metric. Doing so allows the results and values of CI to be more reflective of each PDM's ability to compress a project schedule, a characteristic more indicative of an integrated PDM.

Research Data

The majority of the DBB and DB data for this research stems from a previous research study conducted for the Water Design Build Council (WDBC) by Bogus et. al. (2008), although this research study added several projects to both sample data sets. All of the DBO data used was newly collected specifically for this research. Overall, the data is comprised of 73 DBB, 33 DB, and 38 DBO data points. Each data point is represented by an individual project's PDM and D&C cost and duration values.

After collecting the data, all D&C costs were normalized to 2010 present value using the year each project was substantially completed as the basis for this normalization. Doing so created consistency in the capital cost values so newly completed or current projects would not skew the data. After normalization, outliers were identified and removed using a combination of the Interquartile Range (IQR) detection technique and a qualitative assessment of the data. This cleaned data was used in the statistical comparison presented in Chapter IV.

Research Data Limitations

The most obvious data limitation is the number of data points collected. Although each PDM displays over 30 data points, the more integrated PDMs exhibit are comprised of much less data points than the traditional DBB method. There exist only a limited number of these integrated contracts that are currently underway in the US, and uncovering historical information on these types of projects proved to be difficult, even for project participants. Other limitations surround the D&C capital costs and schedule durations provided by the project participants used to quantify CI. Some participants provided very specific numbers and durations, to the day and dollar, while others provided rounded quantities. Overall, all data was rounded to the nearest month and thousands of dollars for consistency and all results are reported to the accurate number of significant figures.

Results

The results of all three analyses have concluded that the more integrated DBO PDM exhibits a statistically significant and greater degree of CI over DBB and DB projects. Additionally, DB project were shown to exhibit a statistically significant and greater degree of CI over DBB projects in two of the three analyses. In the analysis considering all data points, DBB and DB projects were shown to be statistically equal when comparing the means of CI although the average of DB CI was greater than the average of DBB CI. However, it is important to note that this finding was likely skewed by a large difference between DBO and DBB CI means. Overall, the results indicate there a positive correlation exists between PDM levels of integration and CI. Table D.1 in Appendix D provides a complete overview of all three data analyses and their results.

Arrangement of the Thesis

This Master's Thesis is arranged into five chapters. The chapters begin with an introduction to the study and end with a discussion of the findings and a viable application for the construction industry. The second, third, and fourth chapters present the literature survey, research methodology, and data analysis respectively. Definitions, abbreviations, and literature sources follow the discussion of the research conclusions and application. Appendix A presents the data collection instrument. Appendices B and C are two additional analyses conducted on: 1) the sample sets in their entirety; 2) and the 5 million to 50 million dollar hard cost data range respectively. Finally, the results from all three data analyses are presented in Appendix D.

CHAPTER II

LITERATURE SURVEY

Introduction

This survey of the literature effectively establishes a research background, context, need and point of departure for this study. Information regarding the general history of water/wastewater systems, the history and state-of-practice for the use of PDMs to deliver public infrastructure and water/wastewater utility projects, and the differences, benefits, and limitations between segmented and integrated PDMs with a focus on the DBB, DB, and DBO PDMs was gathered. Because DBO delivery is less understood and utilized by the industry, the benefits and limitations of this PDM are discussed in more detail. This information was collected and aggregated using the following key words:

- Project Delivery Methods;
- Integrated Delivery Methods;
- Alternative Delivery Methods;
- Water/wastewater Utilities;
- Design-Bid-Build Delivery;
- Design-Build Delivery;
- Design-Build-Operate Delivery
- Public Infrastructure

Altogether, the survey was successful in defining the context, need, and point of departure for this research.

Background

General History and Development of Water/Wastewater Systems

Water and wastewater systems boast a rich history of supplying and transporting water to a developing world. As early as 5000 years ago, centralized systems delivering drinking water to communities in parts of the Middle East made their debut (United, 2002). Two and one half centuries later, Athens, Greece became famous for building sewer systems capable of transporting sanitary waste to rural areas for disposal and use in fertilizing orchards and agricultural fields. Since this time, the services of supplying clean water and removing wastewater from cities have become necessities and considered a way of life by communities around the globe (United, 2002). For the US, water supply and wastewater disposal first began with an emphasis on matters related to the transportation and distribution of these products and byproducts. Then, the 1900s brought about an increased concern for human health and the environment, requiring an adjustment from a mindset focused on transportation matters to matters regarding the methods used to treat the water and wastewater products themselves (United, 2002). Now, and for the last century, water and wastewater utilities have become increasingly more advanced in all aspects of providing this service including the transport, treatment, and operations of the facilities and systems. Triggering these advancements are the numerous water policies, acts, and mandates that exist to ensure utilities provide consumers with safe drinking water while simultaneously protecting and minimizing negative impacts to the environment.

Water is essential to life, and throughout the past decade, water utilities have equipped themselves to meet this need by adhering to the fundamental responsibilities of providing clean, reliable, and affordable water to communities (Westerhoff et. al., 2003). Now, utility owners have expanded their responsibilities to include other elements such as meeting customer needs, controlling and reducing costs, and operating and maintaining facilities as efficiently as possible (Westerhoff et. al., 2003). As a result, water utilities provide, treat, and transport water and wastewater more effectively and efficiently than they did just five or ten years ago. However, the vast majority of professionals and consultants agree that these advancements in efficiency will need to increase further in order to sustain a shortage of the financial resources available to meet all the needs and demands placed on the existing systems (Westerhoff et. al., 2003). Clearly, both utility owners and their systems have made significant accomplishments in this area, but there still remains a heavy demand on water/wastewater infrastructure that the current systems cannot bear without additional capital investments.

A Brief History of PDMs Used for Delivering Public Infrastructure in the US

Until the early 20th century, public and private owners employed more *integrated* project delivery techniques to design and construct public infrastructure projects. Typically, owners hired a "master builder" to design, engineer, and construct an entire facility, from beginning to end (Konchar and Sanvido, 1998). For example, the ideas and methods used to design and construct the majority of the large cathedrals in Europe single handedly came from these master builders. Ghavamifar and Touran (2008) have roughly equated history's master builders to today's integrated team builders. Additionally, a study of more than 800 public infrastructure projects dated from 1789 to the Pre-Depression revealed that alternative and "flexible" procurement and delivery strategies completed and successfully operated as many as 90% of these projects before the Second World War (WWII) (Pietroforte and Miller, 2002). It was not until the rise of technology and rapid advancements therein that the design and construction phases of a project production cycle became segmented (Miller, 1997). These advancements began to facilitate the need for an increased level of sophistication in designing, engineering, and constructing different types of facilities and eventually perpetuated the separation of design and construction into more highly specialized services (Konchar and Sanvido, 1998; Miller, 1997). Then, in 1926, the separation of design from construction in public projects using federal funding became mandatory under the Public Buildings Act requiring the approval of complete plans and specifications before the commencement of construction (Pietroforte and Miller, 2002). This then led to the development of a structured project delivery system, which has become known as the traditional "Design-Bid-Build" delivery method.

A Brief History of PDMs Used for Delivering Water/Wastewater Utilities in the US

As a result of the DBB PDM's implementation frequency to deliver all types of public infrastructure projects, water and wastewater projects in the US have also been most frequently delivered using this method. Public utility owners bear a tremendous amount of pressure, from both the media and the public, to continually deliver projects at the lowest capital cost possible. Attempting to deliver these projects with an advanced, complicated, or simply less-understood method then becomes unattractive for these owners who remain under the microscope of taxpayers and the media. For example, a recent survey conducted by R. W. Beck entitled, "Alternative Project Delivery Survey of Water and Wastewater Utilities" revealed that although as many as 90% of water and wastewater utility owners claim to be somewhat familiar with alternative delivery methods, only half have actually delivered a project utilizing a method other than DBB (Bogus et. al., 2008).

Although a reliance on DBB delivery does not promote the interdependence between the public and private sectors on a financial or integrative level, the private sector has always played a role in providing drinking water in the US. Before the 1950s, owners heavily utilized a "dual track" funding strategy in which public infrastructure was being delivered and financed with *both* public and private funds, depending on the availability of public capital at the time (Pietroforte and Miller, 2002). Moreover, within the past ten years, private investors have owned roughly 16% of utilities across the US (Barnes and Meiburg, 2008). In 2006, there was an estimated 15 major drinking water Public-Private Partnerships (P3s) in effect and 29 major clean water P3s (Barnes and Meiburg, 2008). The term "Public-Private Partnership" seems to consistently embody a number of alternative and integrative delivery methods including variations of Design-Build-Operate, Design-Build-Operate-Finance, Design-Build-Operate-Finance-Maintain, and Build-Operate-Transfer (Barnes and Meiburg, 2008). Now, and within the last two decades, more and more water utilities continue to re-evaluate the use of the traditional DBB delivery system and consider the use of more integrated and alternative delivery methods (Westerhoff et. al., 2003).

What is Integrated Project Delivery?

Without a doubt, PDM selection by US public owners has largely favored the more segmented delivery approach with a primary concern for low cost procurement. This translates to the producing entities of a project, including the Architect/Engineer (A/E), builder, operator, maintainer, and financer being wholly separate parties of one another. Although this framework is known for keeping initial D&C capital costs low through a highly transparent and competitive procurement process, it is not the most appropriate method for *all* public projects (Miller et. al, 2000; Miller, 1997). For some projects, employing a more integrated delivery method would result in a greater amount of value to all parties as well as public end users. Project delivery integration is a measure of the degree to which the producing parties are combined together during the project production cycle, allowing for increased benefits over more segmented methods (Miller et. al., 2000). Integrating key project players is not a new or novel concept, but instead part of an "old and forgotten" practice of delivering public infrastructure projects (Pietroforte and Miller, 2002).

Dr. John B. Miller and the Infrastructure Systems Development Research (ISDR) team at the Massachusetts Institute of Technology (MIT) have conducted extensive research and gathered significant amounts of data related to public infrastructure project delivery and procurement methods. Using the data, the research team developed an operational framework to analyze and classify project delivery systems by the degree in which is financed as well as integrated. The degree to which the producing parties are segmented or combined is measured along the horizontal axis, and the degree to which project financing is directly provided by the public owner, or indirectly provided by the project producer or other private entity, is measured along the vertical axis. Figure 2.1 is an overview of the framework.

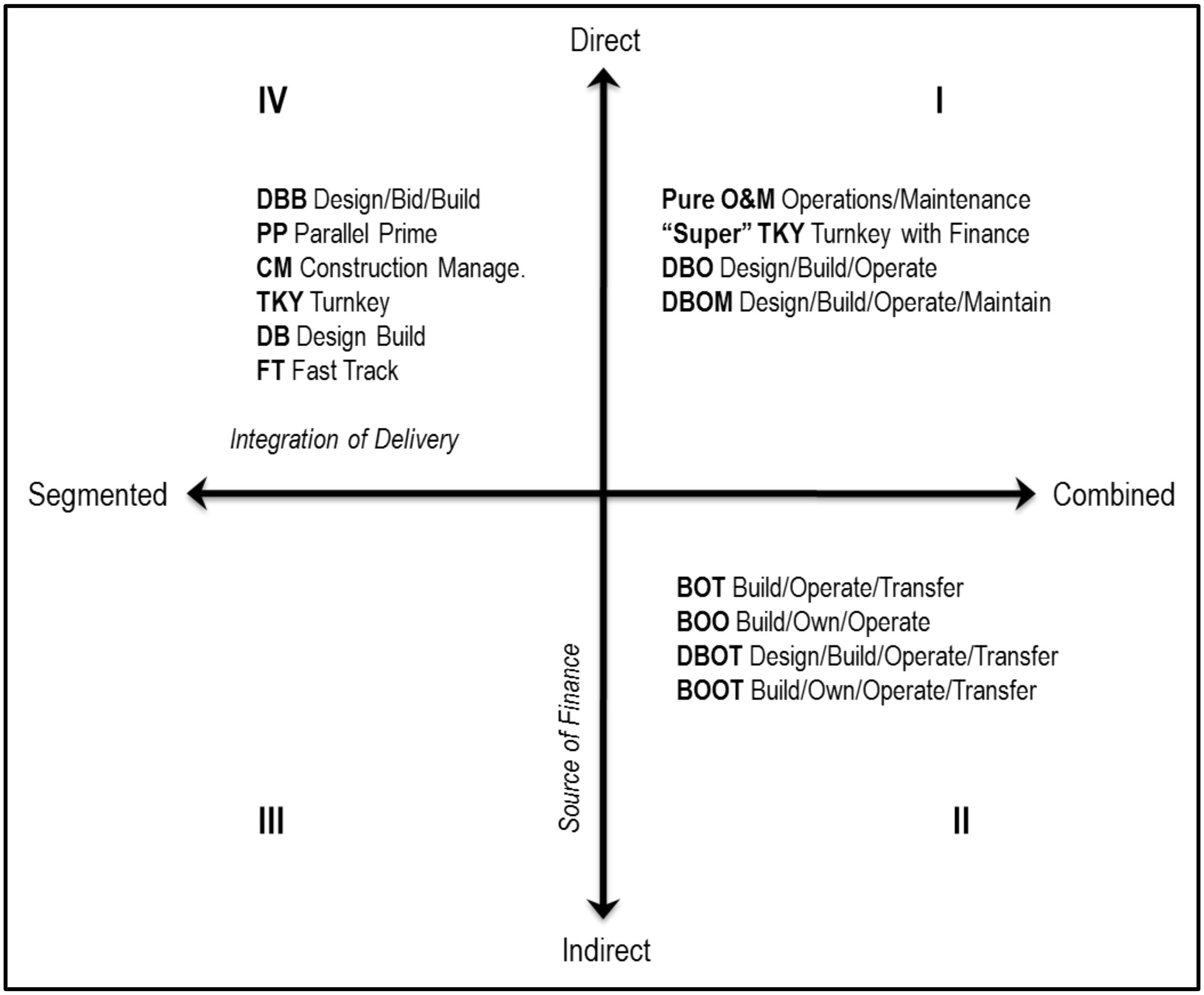

Figure 2.1: Operational Framework for Project Delivery Systems (Miller et. al., 2000)

Segmented and Integrated Project Delivery Methods: DBB, DB, and DBO

The number and variety of delivery methods available for owners and developers to use is greater now than it has ever been. There are fundamental methods that have a long-standing reputation in the industry, while others are only recently receiving recognition. Three delivery methods will be discussed and compared here: 1) Design-Bid-Build; 2) Design-Build; and 3) Design-Build-Operate. The first two methods are considered to be "segmented" according to the Miller et. al. (2000) framework, while the third is considered to be combined or "integrated".

Design-Bid-Build (DBB)

Considered to be the most "traditional" delivery method, owners have heavily utilized DBB to deliver public infrastructure projects in the US since the 1950s (Miller et. al., 2000; Miller, 1997). In executing this type of delivery, the owner selects an A/E to prepare a full set of construction documents for a project. These documents are then used to define a scope of work as well as the selection criteria to be used during the procurement phase in selecting a builder (Konchar and Sanvido, 1998). Generally for projects using public tax dollars, the construction contract is awarded to lowest, responsible, and responsive bidder, unless the owner can justify otherwise. After design and construction is fully complete, the owner assumes responsibility for the operations and maintenance (O&M) of the resulting facility or infrastructure. The project is fully funded and financed by the owner in DBB delivery, and because of this, the owner "owns" the details of the design during construction (Touran et. al, 2011). The focus is primarily on procuring the lowest initial capital costs with an assumption that a continuous stream of future funds to operate and maintain the facility stemming from sources such as taxation and user charges exists (Pietroforte and Miller, 2002). This PDM is considered segmented since the A/E is a separate entity from the builder, who furthermore, is a separate entity from the owner acting as the operator and maintainer of the end facility or infrastructure. This delivery method considers price to be of the highest value in selecting producing parties.

Advantages of DBB

The strengths of this method are clear and widely valued. First, a well-defined scope of work and intense price competition exists during the public bidding process (Miller et. al., 2000; Garvin, 2004). Other benefits include: 1) all parties in the industry generally know and understand the method; 2) systematic checks and balances exist; 3) design changes can be made at a moderate cost as the design phase usually incurs a longer period of time; 4) there is a fixed project price before construction begins; and 5) the contractor assumes the risks related cost and schedule (Bogus et. al., 2008; Garvin, 2004; Westerhoff et. al, 2003). This method also presents the owner with the most control over the design and the relationships between contracting parties, as well as an impartial contractor selection (Gordon, 1994; Garvin, 2004). Additionally, all states allow the use of DBB on both public and private projects (Ghavamifar and Touran, 2008; Pietroforte and Miller, 2002). Furthermore, the US government currently provides preferential legislative treatment through subsidies and other forms of financial support to public owners of public infrastructure projects utilizing DBB delivery (Pietroforte and Miller, 2002). Projects that benefit most from this method are those that can be clearly defined from the onset, do not need to be completed in a short duration, and are unlikely to encounter changes during the construction phase (Gordon, 1994).

Disadvantages of DBB

Although it may be the most widely used and accepted PDM, the limitations of DBB delivery can be significant. For example, the level of collaboration between all producing and financing parties is restricted as a result of the nature of the contractual relationships between each contracting party. Konchar and Sanvido (1998) suggest that information among designers, builders and operators is only being shared at the end of the design phase or during the construction process, and even then, interaction among these key entities is extremely low. This lack of interaction has historically led to inefficient designs, increased errors and disputes, higher project costs, an increased exposure to change orders, and longer project durations (Konchar and Sanvido, 1998; Bogus et. al., 2008).

Not only is collaboration reduced between contracting parties, but the DBB PDM wholly subjects the owner to the limitations of the selected designer. Only one engineering solution, from a single viewpoint, is provided to the owner when in reality, multiple solutions exist with multiple tradeoffs between time, cost, and quality (Miller et. al., 2000; Gordon, 1994). Additionally, it is believed that the method's emphasis on low-price selection increases the probability of leaving owners with unqualified builders during the construction phase (Bogus et. al., 2008; Westerhoff et. al., 2003). Moreover, and perhaps more importantly, the overuse of this traditional method forces owners to align their project goals with the process itself, and consequently restrains project scope to the availability of public money, rather than designing projects to meet long-term public needs (Miller et. al., 2000).

Other significant limitations include: 1) a lack of consideration for life cycle value; 2) insufficient construction knowledge and expertise during the design phase; 3) a lack of innovative design and construction solutions; 4) and a moderate to high probability of disputes occurring as a result of the adversarial relationship that often exists between the designer and builder (Miller et. al., 2000; Gordon, 1994). Finally, since the owner essentially "owns" the details of the project design during construction, it is financially liable for any cost of errors encountered during construction under what is known as the "Spearin Doctrine" by the industry (Touran et. al., 2011).

Design-Build (DB)

Design-Build delivery is similar to the traditional method in many aspects. However, the greatest dissimilarity is that the owner selects a single entity to design and build the project in utilizing the DB PDM, thus resulting in a single point of responsibility and contract agreement for D&C services (Konchar and Sanvido, 1998; Westerhoff et. al., 2003; Ghavamifar and

Touran, 2008). The Design-Builder is generally selected on the basis of qualifications or a two-step procurement process in which proposers are first short-listed according to their qualifications after responding to a Request for Qualifications (RFQ) issued by the owner, and then selected in the second step of procurement after submitting a price and technical solution in response to a Request for Proposals (RFP) (Bogus et. al., 2008). This method of selecting a contracting entity after considering price and technical solutions is often referred to as a "best value" selection since the bidder is selected on the basis of qualifications and other technical criteria *in addition* to price. This is in opposition to selecting a bidder on the basis of price alone (Bogus et. al., 2008; Westerhoff et. al., 2003). The funding and financing responsibilities for the project remain with the owner, as well as the O&M responsibilities (Miller et. al., 2000). Design-Build delivery is still considered segmented by the Miller et. al. (2000) framework since the O&M entity is separate from the design and construction party. However, this method is considered to be more integrated than the traditional DBB method since the designer and builder are contractually combined.

Advantages of DB

The benefits of DB delivery when compared to DBB delivery include: 1) a single point of responsibility and accountability for D&C services; 2) a heightened probability of a reduction in the overall project schedule; 3) an increase in innovation opportunities and constructability as a result of strengthened collaboration and the early involvement of the project builder in the design process; 4) a significant reduction in the probability of change orders between the owner and contractor; 5) a non-adversarial relationship between the designer and builder; and 6) a proactive response to scope changes (Bogus et. al., 2008; Pietroforte and Miller, 2002; Garvin, 2004). There is also a significant decrease in other owner-related costs including transaction and contract administration costs as a result of a reduced number of contracts (Pietroforte and Miller, 2002). Miller and the Barchan Foundation (2010) report that the case study analysis conducted by the ISDR group at MIT on over 800 projects revealed a cost savings of 10% in initial delivery when compared to DBB and a reduction in project schedule duration by 12%. Konchar and Sanvido (1998) found similar results indicating that DB projects yielded cost and schedule reductions of 6.1% and 12% respectively when compared to DBB projects.

Disadvantages of DB

One of the primary limitations of the DB delivery method is the public policies and restrictions in a number of states restraining its use (Pietroforte and Miller, 2002). Other limitations include: 1) the necessity for early owner involvement and decision making; 2) the difficulty associated with defining a scope of work and performance requirements without the benefit of going through a full design process; 3) a reduction in owner control over design details; and 4) a requirement for more upfront capital and cash flow at the onset of the project as a result of the increased speed of project delivery (Bogus et. al., 2008; Garvin et. al., 2000; Westerhoff et. al., 2003; Dahl et. al., 2005). This type of delivery is still considered segmented by Miller et. al. (2000) since the O&M responsibilities of the facility are separate from D&C, minimizing opportunities and incentives for the DB entity to design and build the project with O&M costs and methods in mind.

Design-Build-Operate (DBO)

Design-Build-Operate is similar to the DB delivery method, yet ventures further by integrating the task of O&M into a single contract, usually over a term from 10 to 20 years for water/wastewater projects (Westerhoff et. al, 2003). This has categorized this delivery method as integrated on the Miller et. al. (2000) delivery integration continuum. The DBO contractor is often a joint venture between a DB and an O&M firm and holds a single contract with the owner (Dahl et. al., 2005). In awarding a DBO contract, the owner negotiates a project capital cost and annual or monthly O&M payments for the specified contract period—if the DBO entity exceeds these agreed upon costs, it generally pays out of its own funds. However, if the actual capital and O&M costs are below this agreed upon amount, the excess is profit for the DBO contractor (Dahl et. al., 2005). There are often penalties and incentives built into these contracts dependent on the level of O&M services provided as well as the construction performance of the contractor.

In procuring DBO entities, bidders or proposers respond to a RFQ. The owner then creates a shortlist based on the quality of the responses received. Those contractors that make the list are then solicited a RFP in which price and technical evaluations are assessed, usually by a team of individuals and consultants. There is generally a pre-described method the owner uses to score the proposers, of which the proposers are made aware of prior to submitting their response. Those ranked highest by this scoring method are often asked to enter into negotiations with the owner over price, term, specifications, and even scope. This process is considered "best value" procurement, and is similar to what occurs in DB procurement. Variations of DBO delivery exist regarding the source of financing. Some DBO delivery utilizes public funding entirely, while others use a mixture of private and public sector investments. Instances of using private sector capital or expertise have continually been aggregated under the large "Public-Private Partnership" moniker.

A P3 is an agreement between public and private sectors in which the skills and assets of each, along with project risks and rewards, are shared with the focus of delivering services or a facility to the general public in a highly efficient manner (Sluger and Satterfield, 2010; Ghavamifar and Touran, 2008). It is an evolved variation of DB delivery and a result of the shortage of public funds for public projects, according to some authors (Ghavamifar and Touran, 2008). Others believe that this evolution has occurred as a strategic initiative to capitalize on the assets and expertise of the private sector to deliver and operate projects that are outside the core competency of most owners.

When a DBO entity invests its own capital to support a project, it typically does so at its own risk with the objective of receiving a substantial return on its investment (Miller et. al., 2000; Westerhoff et. al., 2003). This return may come in the form of annual owner payments with additional interest paid to the DBO covering its upfront capital investments, or from generating long-term revenues based on user fees during the operations period. During the operation term, the DBO entity typically "owns", or is granted a full access lease to, the project until the service contract expires. However, during the life of the contract, the public owner is still responsible for setting the rate on user fees, billing, collections procedures, and administrative services (Westerhoff et. al., 2003). After the term is complete, the producer relinquishes the facility over to the owner who then assumes the O&M responsibilities or contracts another party to do so—this may also be done by renewing a pure O&M contract with the previous contractor.

DBO delivery is beginning to increase in popularity as a result of the rise in public dissatisfaction with traditional procurement methods, the development and maturing of the private finance model, and the adoption of "partnering" as a management process (Sluger and Satterfield, 2010). It is being used in instances where the innovative integration of design, construction, long-term O&M and in some cases, finance, are considered influential and necessary to a project's success (Miller, 1997).

Advantages of DBO

Level of Influence over Project Outcomes

It has long been recognized that decisions made early in a project's production cycle have a significantly greater influence on the overall outcomes of a project than decisions made in the later phases (Paulson, 1976). This has been quantified by Paulson's research and cost influence curve presented as Figure 2.2.

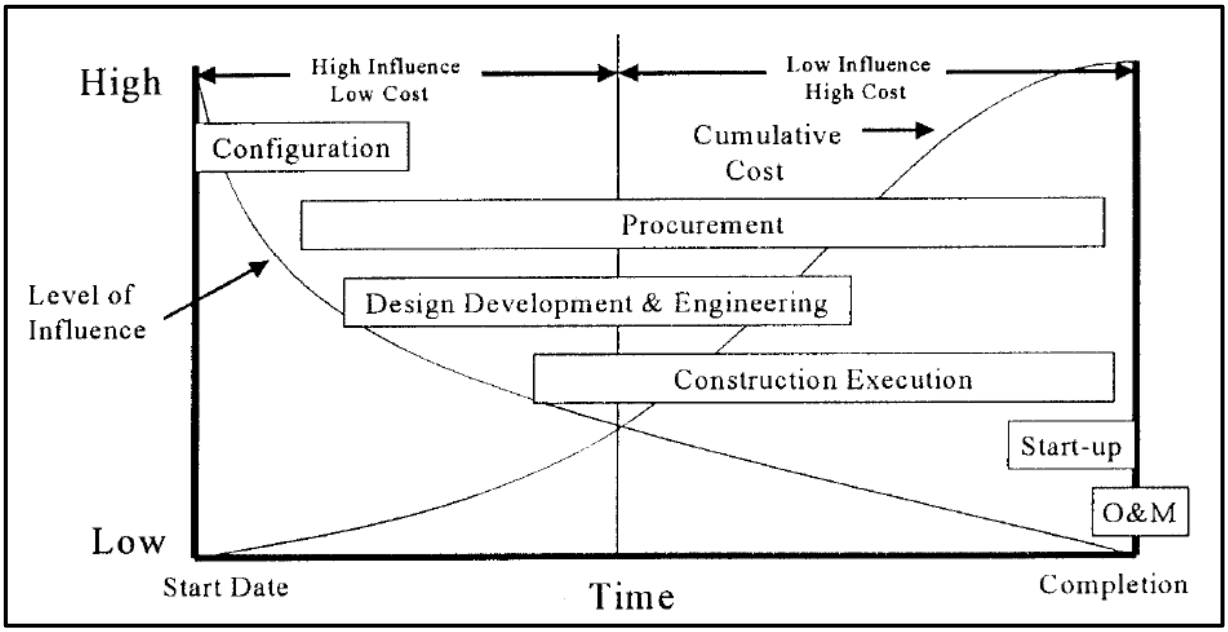

Figure 2.2: Level of Influence throughout a Project Development Cycle (Paulson, 1976)

The figure depicts two curves, the cumulative cost curve shown to increase as the production development cycle matures, and the level of influence curve, shown to decrease along the same time cycle. Paulson's research implies that decisions made earlier in the production cycle are most often low-cost decisions yet have tremendous impacts on project outcomes. Similarly, decisions made late in the production cycle tend to cost significantly more, yet have less ability to alter project outcomes. According to Paulson (1976), after construction begins is when decisions to change or alter a project outcome become more expensive and have diminishing impact.

It is clear that decisions made during the programming/planning and design development phases of a project production cycle have the ability to generate largely positive or negative outcomes. This finding remains true for water and wastewater utility projects as well. Integrated delivery methods allow project producers and owners to capitalize on this effect by bringing in more parties and points of view at earlier phases in the production cycle. Having more parties involved from the onset of a project significantly increases the probability of generating new innovative ideas and solutions. For example, Westerhoff et. al. (2003) believe the degree to which individuals who harness the different skills of design, construction, and O&M can work collaboratively, especially during the early design phase, the greater the probability of a successful utility project. Although in more segmented delivery method there are often attempts to increase and foster this collaboration through the use of exercises such as constructability reviews, value engineering discussions, and operability reviews, the greatest degree of integration and "synergy" occurs when the contractor is also responsible for the O&M of the facility (Westerhoff et. al., 2003)

Introduction of Innovative Technologies and Increased Competition for All Phases

Among the most commended advantages integrated delivery offers the industry is the opportunity to introduce new technologies, innovations, and ways of thinking from the private sector into the public sector (Miller et. al., 2000). According to Garvin (2004), an integrated producing party possesses a greater ability and incentive to introduce innovative technologies during the design phase when compared to a producer contracted in a segmented PDM where the designer cannot foresee who will build the project and has little incentive to propose unproven technologies for construction and O&M. The private sector is continually developing new technologies and methods that make infrastructure less expensive to install, build, operate, and maintain, and harnessing this knowledge and technology for the public sector often results in three primary benefits: 1) the owner is delivered a project of higher quality within a given budget and time constraint; 2) the producers are given the opportunity to expand their innovations and be recognized for their successes in doing so; and 3) the end users of the product often receive higher levels of service (Slugger and Satterfield, 2010). Additionally, owners are rewarded with an increased level of competition for all phases when pooling competition for the entire production cycle into a single procurement process (Garvin, 2004; Miller and Barchan Foundation, 2010; City, 2010).

Reduced Capital Costs & Schedule and Increased Constructability

Gordon (1994) recognized that integrating design with construction has been shown to significantly reduce project durations. The reasons for this are twofold: 1) overlapping D&C fosters a sense of teamwork between producing parties and the owner, expediting the process and providing flexibility to handle changes; and 2) this overlap reduces the time needed to bid out and procure the project D&C phases separately (Westerhoff et. al., 2003; Pietroforte and Miller, 2002; Bogus et. al., 2008; Gordon, 1994). Figure 2.3 presents a high-level comparison of a hypothetical project being delivered three different ways: Traditionally, with the DB method, and with the DBO method. Clearly, DBO exhibits the highest degree of schedule compression.

<table>
<tr><th>Quarter</th><th>DBB</th><th>DB</th><th>DBO</th></tr>
<tr><td>1</td><td rowspan="4">Government Planning Viability
Project Advertising</td><td rowspan="4">Government Planning Viability
Project Advertising</td><td rowspan="4">Government Planning Viability
Project Advertising</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td></tr>
<tr><td>5</td><td rowspan="2">Design Competition</td><td rowspan="3">Design Build Competition</td><td rowspan="2">Permitting</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td><td rowspan="4">Complete Design</td><td rowspan="2">Single Competition 30% Design</td></tr>
<tr><td>8</td><td rowspan="4">Complete Design</td></tr>
<tr><td>9</td><td rowspan="3">Finish Design</td></tr>
<tr><td>10</td></tr>
<tr><td>11</td><td rowspan="4">Permitting</td></tr>
<tr><td>12</td><td rowspan="4">Permitting</td><td rowspan="13">Construction</td></tr>
<tr><td>13</td></tr>
<tr><td>14</td></tr>
<tr><td>15</td><td rowspan="2">Construction Completion</td></tr>
<tr><td>16</td><td rowspan="13">Construction</td></tr>
<tr><td>17</td><td rowspan="16">Construction</td></tr>
<tr><td>18</td></tr>
<tr><td>19</td></tr>
<tr><td>20</td></tr>
<tr><td>21</td></tr>
<tr><td>22</td></tr>
<tr><td>23</td></tr>
<tr><td>24</td></tr>
<tr><td>25</td><td rowspan="9">Operations</td></tr>
<tr><td>26</td></tr>
<tr><td>27</td></tr>
<tr><td>28</td></tr>
<tr><td>29</td><td rowspan="5">Operations</td></tr>
<tr><td>30</td></tr>
<tr><td>31</td></tr>
<tr><td>32</td></tr>
<tr><td>33</td><td>Operations</td></tr>
</table>

Figure 2.3: Comparison of PDM Schedule Durations (Pietroforte and Miller, 2002)

Miller and the Barchan Foundation (2010) report that, on average, projects integrating design, construction, and O&M see a cost savings of 30%-40% over DBB and 25% reduction in project schedule. Furthermore, allowing for early contractor involvement during the design serves to augment the designer’s construction experience and provide insight into important tasks such as value engineering, constructability reviews, and cost estimating, ultimately leading to a more "constructable" and affordable project.

Reduction in O&M Costs

Dahl et. al. (2005) believe that O&M knowledge must be incorporated early in the design phase in making critical design decisions. Delivery methods have a significant impact on the manner in which teams come together and the decisions that are made—those that integrate design and construction with O&M bring critical O&M knowledge into the design phase, resulting in a more efficient and sustainable facility for the owner, operator, and end users. For example, when only one percent of project's initial capital costs are spent, as much as 70% of its life cycle costs may already be committed based on that decision.

Over the life of a typical facility, the O&M costs significantly outweigh the initial capital costs (Dahl et. al., 2005). For example, the study of 800 public infrastructure projects by the ISDR group at MIT found that, both on average and conservatively, for every dollar spent on design, ten dollars are spend on construction, and 100 dollars are spent on O&M (Miller and Barchan Foundation, 2010). Because water and wastewater facilities and systems typically boast a useful life of anywhere from 30 to 50 years, the costs to operate and maintain these facilities over their lifespan must be considered as they make up a significant portion of the total, overall costs. The EPA's "Estimating Water Treatment Costs Volume 1" provides a rough estimate of construction and O&M costs for a conventional 40 Million Gallon per Day (MGD) water treatment plant. An overview of the breakdown of these average costs is provided in Table 2.1.

Table 2.1: Cost Breakouts for Conventional Water Treatment Plants (EPA, 1979)

40 MGD Conventional Water Treatment Plant Costs	
Description	**Estimate**
Construction	$2,663,650
Energy	547,320 kwh/yr
Maintenance	$13,020/yr
Labor	13,558 hr/yr
Diesel Fuel	7820 gal/yr

Includes rectangular clarifiers (1000gpd/ft^2, 40,000ft^3), Basket Centrifuge (115,000gpd) and dewatered sludge hauling (20miles at 20,000yd^3/yr)

Although the data is dated, it illustrates a need for considering O&M costs when estimating the total cost of a water/wastewater facility. It can only be speculated that all these costs have increased as time progressed with the emergence of new and more expensive technologies and inflation rates. However, the breakdown and proportion of O&M costs to construction costs has likely remained the same. The O&M costs as well as energy costs during this phase contribute to a significant portion of overall total project costs, and should therefore be heavily considered early on in the production cycle to take advantage of Paulson's research findings. Additionally, integrating D&C and O&M knowledge allows owners and producers to capitalize on the unique capabilities of the entity slated to provide the O&M services for a project, further reducing the costs associated with O&M (Dahl et. al., 2005).

Higher Levels of Service and Increased Asset Management

Although Miller et. al. (2000) have clearly demonstrated and quantified an owner focus on initial capital costs for the majority of public infrastructure projects, Westerhoff et. al. (2003) have recognized a recent shift in the water/wastewater sector to highly value the level of service provided to end users. The key to providing higher levels of service precedes the operations phase of the production cycle and begins in the design phase. Facilities must be *designed* to provide high levels of customer service, not simply *operated* to do so. Integrating design with construction and operation would logically encourage producers to account for both constructability and ease of operations during design, a tremendous benefit for public owners who are at the mercy of design decisions for 30 to 50 years (Garvin, 2004).

Effectively managing assets is critical to harnessing the long-term ability to provide high levels of quality service to end users at an affordable rate (Westerhoff et. al., 2003). In order to do this, owners must additionally shift their focus towards asset management, and this focus must begin early in the production cycle—as early as in the business and strategic planning processes (Westerhoff et. al., 2003). Asset management must drive specific service needs and determine the priority of potential projects to meet these needs (Westerhoff et. al., 2003). This helps decision-makers identify, prioritize, and fund those projects that can significantly reduce overall life-cycle costs, increase asset life, decrease maintenance costs, and decrease capital costs (Westerhoff et. al., 2003). Utilities that have established a formal asset management program report savings of anywhere from five to 20% over an asset's useful life (Westerhoff et. al., 2003). The benefits of asset management have been recognized to be so substantial that, in Australia, it has become policy for utility owners to develop comprehensive asset management plans that link capital costs, maintenance costs, and levels of service for water/wastewater utilities (Westerhoff et. al., 2003). Integrated PDMs allow for more formalized asset management processes that reduce life cycle costs and improve quality since integrating D&C with O&M establishes an incentive for the contractor to design facilities to operate as efficiently as possible to save both itself, and consequently, the owner both time and money (Garvin, 2004; Pietroforte and Miller, 2002).

Risk Allocation and Alternative Sources of Capital

The producing party of an integrated PDM guarantees the performance of the full-service contract, shifting the risk for the design, construction, operation, and maintenance of the facility to the private entity (Sluger and Satterfield, 2010 and City, 2010). This holds the producing party responsible for converting uncertain O&M expenses into known payments, providing the owner with fixed and predictable short and long-term costs, and preventing unexpected cost increases (Garvin, 2004; City, 2010). Table 2.2 presents a summary of the risk transfer that occurred in a recent integrated contract agreement to deliver a seawater desalination plant in Australia in 2009. The State of Victoria is the owner of the project, and a private entity is the integrated concessionaire. Note that the vast majority of risks, specifically those regarding D&C, O&M, asset management, finance as well as water output volume and quality, are borne by the contracting party.

Table 2.2: Risk Allocation for the Delivery of a Seawater Desalination Plant (Capital, 2009)

Type of Risk	Description	O*	C*
Site Risks			
Land Acquisition	Risks associated with acquiring interests in land required for the project design, accepted by the State	✓	
Key Approvals	The risk of delay in obtaining, or delay to the Project resulting from legal action, revocation or amendment of, specified Key Approvals for the Project.	✓	
Other Approvals	All risks of obtaining any other necessary approvals, consents, permits, licenses, etc. for the Project, including any additional cost or delay to the Project in obtaining those approvals, or if those approvals are subject to unanticipated and onerous conditions, or are challenged.		✓
Site Conditions	Risks of geotechnical, marine and other site conditions.		✓
Environmental Contamination	Risk of contamination on Project sites.		✓
Native Title Claims and Artifacts	Risk of cost and delay if native title claims are made or native title is found to exist, or if work must be suspended due to the discovery of artifacts on the site.	✓	
Scope Risks			
Output Specification and Project Requirements	Risk that the State's output specification (as set out in the Project Requirements) does not meet the State's requirements, including if the capacity of the Project is not adequate to meet the State's needs.	✓	
Design, Construction, and Commissioning Risks			
Design and Construction Risk	Risk that the design, construction and commissioning of the Project cannot be completed on time or to budget (other than as specified below), or that the Project (as built) does not meet the State's output specification resulting in delayed or reduced service to the State.		✓
Force Majeure Events and Extension Events	Risk of delay to completion and increased construction costs caused by force majeure events or specified extension events (State risk items) such as State breach, court decisions preventing the Project and change in law.	✓	✓
Power Supply Infrastructure	Risk that sufficient power supply infrastructure is available to supply electricity during the construction phase.		✓

Type of Risk	Description	O*	C*
Water Supply System Connection Risk	Risk that there is a delay to completion of the Project and commencement of delivery of water attributable to a delay in Melbourne Water completing the preparatory works at the main delivery point near Cardinia Reservoir.	✓	
Operational Risks			
Operation, Maintenance and Repair	Risk that the requirements for operation, maintenance and repair to meet the State's specification are different or cost more than anticipated (subject to the risks identified below).		✓
Design Risks	Risk that the design and technology are incapable of delivering Project services at required service levels.		✓
Input Seawater Characteristics	Risk associated with the characteristics of input seawater.		✓
Output Volume and Quality Risk	Risk that the quantity and quality of desalinated water supplied to the Delivery Points does not meet the State's requirements.		✓
Discharge Risk	Risk associated with EPA or any other requirements existing at Contractual Close concerning the quality and rate of environmental discharge, including diffusion of concentrate or sludge discharge.		✓
Power Supply Risk	Risk that sufficient power supply is available to supply electricity during the operation phase.	✓	✓
Electricity and Renewable Energy Credits Consumption and Costs	Risk that the cost and consumption of electricity and renewable energy credits required for the Project differs to that anticipated.		✓
Water Supply System	Risk that the State's water supply system is unavailable for a prolonged or unanticipated period of time to receive desalinated water from the Project.	✓	
Water Supply System Damage	Risks of damage to the State's water supply system caused by the Project.		✓
Force Majeure	Risk that force majeure events affect the Project during the operating phase.	✓	✓
Industrial Relations			
Industrial Action	Risks of all strikes or industrial action, except as identified below.		✓
	Risks of strikes or industrial action directed at the Project during the construction or operating phase, if it can be reasonably demonstrated that the action results from a wrongful act or omission of the State directly in connection with the Project.	✓	
Asset Risk			
Asset Ownership, Maintenance and Life Span	Risks associated with the maintenance and ownership of assets – including the requirement to maintain assets in order to deliver the Project services, and that Project assets do not have the required asset lives.		✓
Upgrades Due to Technological Innovation	Risks associated with implementing Project upgrades consistent with market practice.		✓
Handover Risk	Risks associated with satisfying the State's requirements regarding asset condition and residual design life at the end of the Project Term.		✓

Change in Law			
Specified Changes in Law	Specified changes in law, including changes to Part IVAA of the *Wrongs Act 1958* (Vic), changes to reference documents set out in the State's Project Requirements, implementation of the carbon pollution reduction scheme, enactment of the draft Environmental Protection Regulations for Industrial or Prescribed Waste or the *Fair Work Bill 2008*, changes in tax law, or other changes reasonably foreseeable when the contracts were entered into.		✓
Other Changes in Law	Risk of other changes in law.	✓	✓
Sponsor and Finance Risk			
Interest Rate and Foreign Exchange Risk Prior to Financial Close	Risk of movements in interest or foreign exchange rates between bid submission and Financial Close.	✓	
Interest Rate and Foreign Exchange Risk After Financial Close	Risk of movements in interest or foreign exchange rates after Financial Close.	✓	✓
Cost Movements Prior to Financial Close	Risk of movements in the cost between bid submission and Financial Close.		✓
Construction Phase Insurances	Risk of changes to pricing of construction phase insurance.		✓
Operations Phase Insurances	Risk of changes to pricing of operations phase insurance.	✓	✓

*O Represents the Owner
*C Represents the Integrated Concessionaire

Moreover, harnessing the financial power, flexibility, and capability of the private sector increases the benefits to the owner in terms of funding large projects quicker than traditional methods allow (Sluger and Satterfield, 2010; Gordon, 1994; Papajohn et. al., 2010). Arrangements in which the producer provides upfront capital for projects that cannot support themselves preserves the owner's capital for use in other projects as well as providing instant access to cash flow to initiate a project (Garvin, 2004; Pietroforte and Miller, 2002).

Disadvantages of DBO

Need for Private Sector Incentives

Among the most substantial limitations of integrated project delivery is convincing private sector producers to bid on public projects. The quality of the end product and levels of services provided are dependent on the selection availability of private sector producers who are willing to participate in a bidding process that is fundamentally more involved and costly than traditional procurement (Westerhoff et. al., 2003; Miller et. al., 2000; Slugger and Satterfield, 2010; Papajohn et. al., 2010). Moreover, the private teams entering the bidding process are often expected to wholly bear the potential upfront capital risks of the project, which can total to millions of dollars in some cases (Sluger and Satterfield, 2010). Because of this, there must be an incentive for more private sector leaders and innovators to offer their expertise, technology, and new ways of thinking to the public sector at such a high cost and risk. A significant incentive identified by authors is transparency in the procurement process as well as set of well-defined criteria for proposal evaluation.

Lack of Transparency in the Procurement Process

Transparency in the procurement process is not as well defined for integrated PDMs as it is in traditional DBB. However, the level of understanding and standard of transparency showcased by the DBB PDM must be the goal for integrated PDM procurement (Garvin, 2004). To encourage private sector competition, owners ought to demonstrate that they will treat private sector participants in a stable and predictable fashion; otherwise, private sector participants will pursue more attractive markets elsewhere (Miller et. al., 2000; Garvin, 2004; Wibowo and Kochendoerfer, 2010). Indicating objective producer selection criteria during the procurement phase may be a way to do this, as firms will know exactly what the premise of selection is, and whether or not it is worthwhile to submit a proposal (Miller et. al., 2000). Without clear evaluation criteria for the selection of producers, a fair comparison and the determination of what is most valuable to the owner and the public deteriorates. Consequently, if public owners are selecting private sector participants to deliver public projects, the customers and end users will need to see accountability and competition in the process to assure that public dollars are being properly and ethically invested. A lack of interested private producers in the process is likely to trigger insecurity and criticism towards the process by the general public.

Decreased Owner Influence and Need for Increased Owner Sophistication

In addition to competition limitations, owners face other limitations as well. As the level of integration for a PDM increases, the owner's ability and capacity to manage certain aspects of a project decreases (Westerhoff et. al., 2003; Dahl et. al., 2005; Miller et. al, 2000). Integrated delivery requires the owner to relinquish its control and responsibility over the design of the utility, including processes and equipment selection, to the private entity. Although this increases the range of latitude for innovation and creativity in the design process, it may not always result in the highest quality end product (Westerhoff et. al., 2003). Not only does an owner have less control over each production cycle phase, but owners must also exhibit a greater amount of sophistication and knowledge regarding all aspects of the project, including financing strategies.

Furthermore, recent evidence shows that public owners are unprepared to execute workable concessions with the private sector as a result of misconceptions and misunderstandings regarding the characteristics and applications of alternative delivery strategies (Garvin, 2004). The assumption that all public owners currently possess an adequate level of understanding of each integrated or segmented delivery method, its benefits, limitations, and appropriate applications is untrue. In general, public owners are most familiar with the traditional delivery method. Encouraging increased PDM education may be difficult, especially for owners who believe DBB is still the most appropriate method for every application. Additionally, the integrated delivery methods involving mixed public and private financing, or solely private financing, will require a greater degree of sophistication and the need to develop cash flow and financing models during the planning phase. This requires owners to add additional staff with specialized expertise or outsource these processes to external consultants

(Miller, et. al. 2000). Both alternatives require additional capital to be expended, which further limits the attractiveness of integrated PDM execution.

Restrictions on the Use of Alternative PDMs

A number of states in the US do not allow the use of alternative PDMs in place of the traditional DBB method (Ghavamifar and Touran, 2008; Barnes and Meiburg, 2008). Additionally, in those states that *do* allow the use of alternative PDMs, a requirement for extra approvals from public owners and agencies before implementation, even from entities outside the agency, usually precedes this allowance (Ghavamifar and Touran, 2008). Furthermore, in the majority of instances, privately owned water and wastewater facilities are not eligible for state and federal subsidies. These constraints, coupled with nature of uncertainty regarding the financing mechanisms, often oppose the necessities of integrated delivery and finance and may limit terms on contracts, take-or-pay agreements, or may fail to authorize private parties to collect service fees (Barnes and Meiburg, 2008; Papajohn et. al., 2010; Ghavamifar and Touran, 2008). All these restraints would require a change or revision in legislation and regulations, often a long and drawn out process. The misunderstanding and misrepresentation of the characteristics and implications of integrated delivery systems are also creating restrictions as they continually lead more owners towards relying solely on the better-understood DBB method. Until these are cleared, integrated delivery systems will remain underused as a viable tool for improving project efficiency, costs, and level of services delivered to the public (Garvin, 2004).

Public Perceptions of Alternative PDMs

Finally, another significant barrier to integrated PDM implementation is the general public's perception of alternative PDMs and the objections that follow. A lack of familiarity with this delivery and skepticism related to the advantages it claims have created distrust in the private sector's ability to deliver services as monumental as clean drinking water and wastewater management (Barnes and Meiburg, 2008). Compounding the issue is the public's preconceived notion that it is the government's responsibility to provide these services, and that involving the private sector will only result in higher rates and user charges for the same quality of service (Barnes and Meiburg, 2008; Papajohn et. al., 2010). Furthermore, the belief that a future immersed with private sector involvement in public projects will result in: 1) a complex network of infrastructure with varied ownerships and pay schemes; 2) increased user costs; and 3) potential foreign ownership are all byproducts of a lack of understanding for integrated PDMs and may be impeding utilization (Papajohn et. al., 2010).

Table Summaries of Advantages and Disadvantages

All the information collected through the literature survey regarding the benefits and limitations of DBB, DB, and DBO delivery is summarized in the tables below. The majority of the benefits and limitations have multiple authors and sources supporting them—these tables show which authors converge on similar ideas and findings. Table 2.3 aggregates the advantages and disadvantages for segmented PDMs while Table 2.4 aggregates the advantages and disadvantages for integrated PDMs.

Table 2.3: Aggregated Results Regarding the Strengths and Weaknesses of Segmented PDMs

Strengths and Weaknesses of Segmented Delivery Methods	
Strengths	**Source**
Owner Retains Heavy Project Influence	Garvin, 2004: Gordon, 1994
Periodic Decision Points—Opportunities to Stop Project Before Committing to Construction	Garvin, 2004: Miller and Barchan Foundation, 2010
Highly Competitive and Impartial Contractor Selection	Garvin, 2004: Miller et. al., 2000: Gordon, 1994
Low Cash Requirements During Design	Miller and Barchan Foundation, 2010: Garvin et. al., 2000
Well Defined Scope of Work and Fixed Project Price at the Time of Bidding	Garvin, 2004: Miller et. al., 2000: Dahl et. al., 2005: Bogus et. al., 2008: Westerhoff et. al., 2003: Gordon, 1994
Well Known and Understood by the Industry	Bogus et. al., 2008: Garvin, 2004: Westerhoff et. al., 2003
Systematic Checks and Balances	Bogus et. al., 2008: Garvin, 2004: Westerhoff et. al., 2003
Contractor assumes Risks for Cost and Schedule	Bogus et. al., 2008: Garvin, 2004: Westerhoff et. al., 2003: Dahl et. al., 2005
Preferential Legislative Treatment	Pietroforte and Miller, 2002: Ghavamifar and Touran, 2008
Weaknesses	**Source**
Interaction/Collaboration Between key parties is Limited	Konchar and Sanvido, 1998: Miller et. al., 2000
Inefficient Designs and Increased Probability of D&C Errors	Konchar and Sanvido, 1998: Bogus et. al., 2008
Increased Probability of Disputes Between Key Parties	Konchar and Sanvido, 1998: Bogus et. al., 2008: Miller et. al., 2000: Gordon, 1994
Increased Project Costs and Schedule Durations	Konchar and Sanvido, 1998: Bogus et. al., 2008: Dahl et. al., 2005
Increased Exposure to Change Orders	Konchar and Sanvido, 1998: Bogus et. al., 2008
A/E Solution From a Single Viewpoint	Miller et. al., 2000: Gordon, 1994
Increased Probability of Selecting an Unqualified Builder	Bogus et. al., 2008: Westerhoff et. al., 2003
Lack of Consideration for Project Life-Cycle Value	Miller et. al., 2000: Gordon, 1994

Lack of Construction Knowledge and Expertise During Design	Miller et. al., 2000: Gordon, 1994
Owner is Responsible for Errors Encountered During Construction—"Spearin Doctrine"	Touran et. al., 2011

Table 2.4: Aggregated Results Regarding the Strengths and Weaknesses of Integrated PDMs

Strengths and Weaknesses of Integrated Delivery Methods	
Strengths	**Source**
Higher Degree of Team Communication and Coordination	Westerhoff et. al., 2003: Dahl et. al., 2005: Konchar and Sanvido, 1998: Ghavamifar and Touran, 2008: Bogus et. al., 2008: Pietroforte and Miller, 2002
Reduced Administrative Burden for Owner	Westerhoff et. al., 2003: Miller et. al., 2000: Miller, 1997: Pietroforte and Miller, 2002
Constructability and O&M Reviews During Design	Dahl et. al., 2005: Garvin, 2004
Higher Potential for Savings in Capital and Time	Westerhoff et. al., 2003: Garvin, 2004: Bogus et. al., 2008: Pietroforte and Miller, 2002: Gordon, 1994: Capital, 2009
Innovation and New Technology Opportunities	Westerhoff et. al., 2003: Garvin, 2004: Miller et. al., 2000: Capital, 2009
Guaranteed Performance from Design Through O&M	Westerhoff et. al., 2003
Introduction of Private Sector Practices into Public System (Shared Learning Experiences)	Westerhoff et. al., 2003: Miller et. al., 2000: Garvin, 2004
Integration of Lifecycle and O&M Information into Design	Garvin, 2004: Dahl et. al., 2005: Capital, 2009
Opportunity to Design for the Unique Capabilities of the Entity Providing O&M Services	Dahl et. al., 2005
Incentive for Contractor to Design and Construct the Facility to Minimize O&M Costs	Dahl et. al., 2005: Garvin, 2004: Pietroforte and Miller, 2002: Capital, 2009
Lifecycle Cost Competition	Garvin, 2004: City, 2010: Miller, 2010
Cost Certainty During O&M Period	Garvin, 2004: Dahl et. al., 2005: City, 2010
Significant Risk Shift from Owner to Contractor	Dahl et. al, 2005: City, 2010: Sluger and Satterfield, 2010: Capital, 2009

Weaknesses	Sources
Reduction in Owner Influence over the Project Outcomes	Westerhoff et. al., 2003: Dahl et. al., 2005: Bogus et. al., 2008: Miller et. al., 2000
Procurement Process is Significantly More Complicated and Costly	Westerhoff et. al., 2003: Miller et. al. 2000: Sluger and Satterfield, 2010: Papajohn et. al., 2010
Legislative Restrictions	Westerhoff et. al., 2003: Pietroforte and Miller, 2002
Difficulty in Attracting Private Sector Involvement	Westerhoff et. al., 2003: Wibowo and Kochendoerfer, 2010: Miller et. al., 2000
Independent Engineers Often Necessary	Garvin, 2004
Complicated Handover Processes	Garvin, 2004
Limited Experience with Integrated PDMs in the US	Garvin, 2004: Dahl et. al., 2005: Miller et. al., 2000
Higher Initial Cash Flow Demands	Garvin et. al., 2000: Bogus et. al., 2008
Negative Public Perceptions	Barnes and Meiburg, 2008: Papajohn et. al., 2010

Conclusion and Point of Departure

The literature survey successfully established the context for this research by collecting information related to the general history of water/wastewater systems, the history of public project delivery methods in the US in general as well for water/wastewater utilities specifically, integrated project delivery methods, and the differences, benefits, and limitations between segmented and integrated PDMs. It is clear that there are significant differences in the advantages and disadvantages of segmented and integrated PDMs. In 2008, Bogus et. al. conducted a research endeavor to help quantify a number of these differences.

Bogus et. al. (2008) determined a correlation between numerous project performance measures surrounding cost and schedule and the DBB and DB PDMs for water and wastewater utility projects. One of the performance measures used and compared was CI, a measure of

D&C costs over D&C duration. The findings were significant and revealed clear differences in the ability of DBB and DB PDMs to deliver projects at a specified cost and within a specific schedule. It also determined that, on average, DB projects exhibited a statistically higher level of CI than their DBB counterparts. It was decided that extending this previous research to include the comparison of DBB and DB projects with more integrated DBO projects would be an interesting and useful endeavor for the water/wastewater sector. To make this extension, the Miller et. al. (2000) framework was used to classify PDMs on the basis of integration.

CHAPTER III

RESEARCH METHODOLOGY

Introduction

The methodology guiding this research is a formal research approach known as the Center for Integrated Facility Engineering (CIFE) research "Horseshoe". The Stanford University Civil Engineering program developed this research approach. The CIFE Horseshoe was determined to be the most comprehensive and appropriate methodology to meet the goals of this research and a broad overview of the methodology is presented as Figure 3.1.

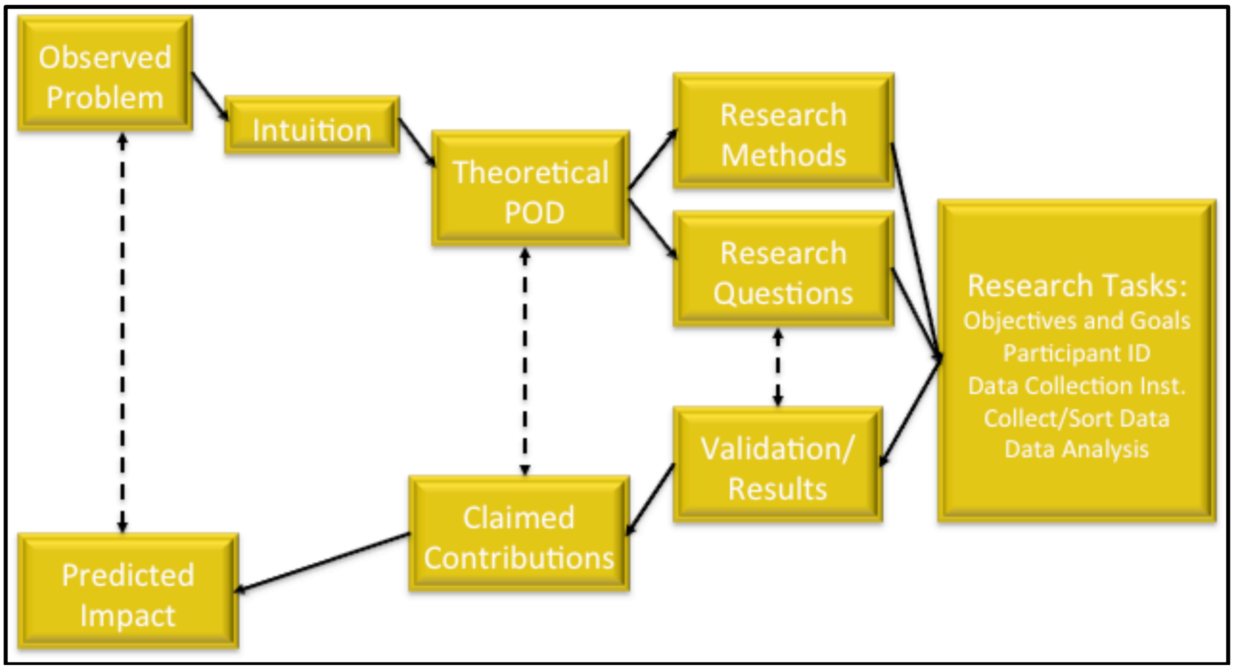

Figure 3.1: Overview of CIFE Horseshoe Research Methodology (Kunz and Fischer, 2007)

Each of the following subsections further describes each methodology step and how they were applied to this research.

Observed Problem

The observed problem for this study is rooted in the Bogus et. al. (2008) study conducted for the Water Design Build Council. The study concluded that DB projects exhibit a higher degree of CI than DBB projects on average. However, according to the Miller et. al., (2000) framework, both the DBB and DB PDMs are considered segmented delivery methods. Therefore, this study utilized the same performance metric, CI, but made a comparison between segmented PDMs and the integrated DBO PDM to determine if the correlation is dependent on the degree of delivery method integration.

Construction intensity is a performance measure related to a project's D&C cost and duration and can be used to measure the efficiency of a project's performance. Specifically, it is a measure of the amount of money expended over a specified period of time and is an attempt to combine cost, time, and project size into a single metric. Gransberg and Buitrago (2002) have defined this project performance measure as a dynamic metric since it is project size dependent and variable with time.

Intuition

The anticipated outcome of this study was that the data would reveal a positive correlation between CI and the level of integration inherent in the DBB, DB, and DBO PDMs. This is to say that a project delivered under a more integrated PDM, such as DBO, would exude a greater value of CI than a project that is delivered under a more segmented delivery method such as DBB. It is expected that this pattern will apply across the majority of projects in all three PDM categories. This anticipation emanates from the conclusions of the Bogus et. al. (2008) study which determined DB projects displayed a higher degree of CI than DBB projects. Additionally, the aggregation of the benefits and limitations of segmented versus integrated PDMs found in the literature also helped shape this intuition as a number of these findings impact cost and duration, the variables influencing CI. Figure 3.2 is a graphical representation of these anticipated outcomes.

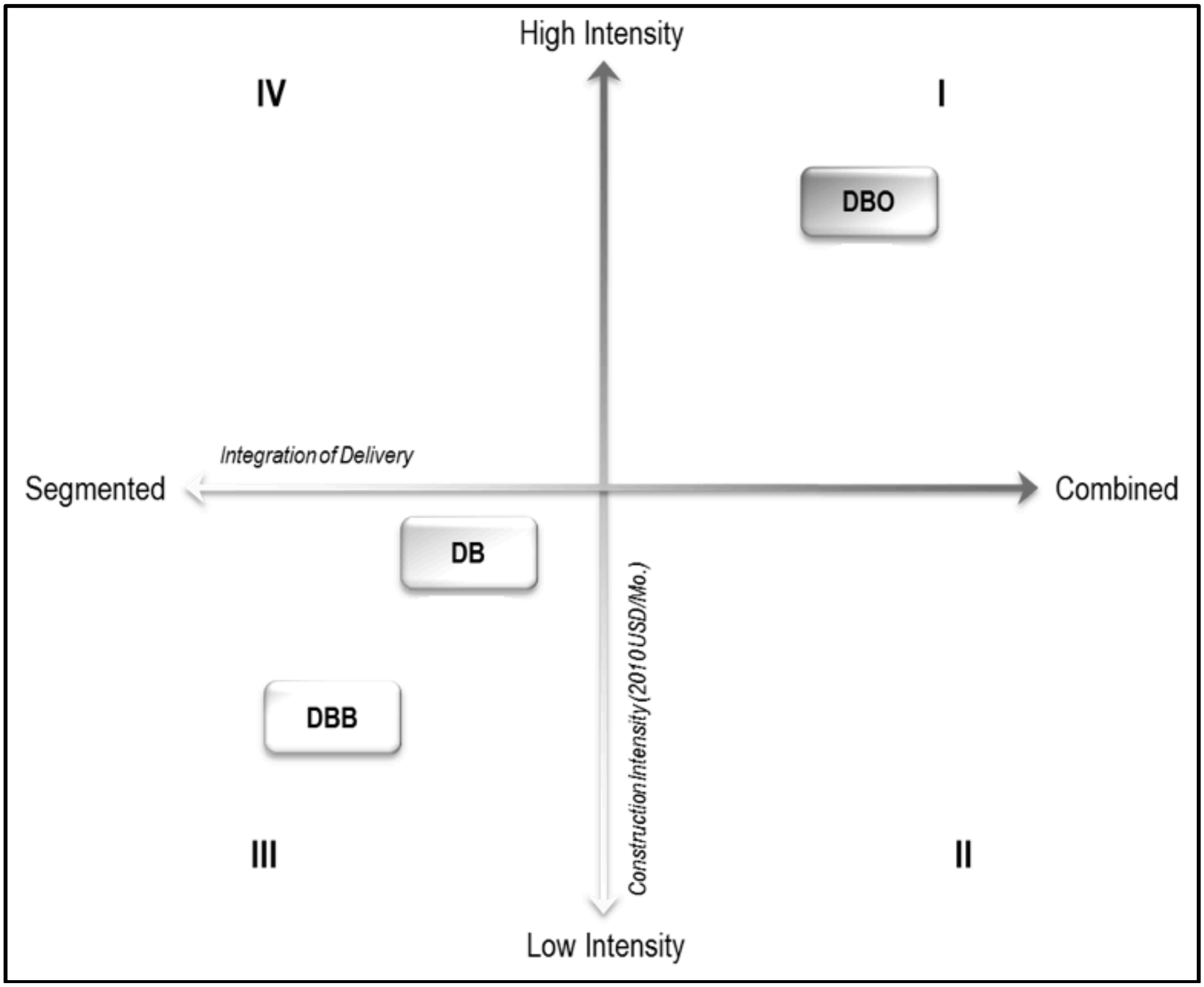

Figure 3.2: Anticipated Correlation between CI and Level of PDM Integration

Theoretical Point of Departure

As previously discussed, the point of departure for this study is an expansion of the existing Bogus et. al. (2008) study to incorporate the DBO PDM into the comparison of delivery methods using the CI performance metric introduced by Konchar and Sanvido in their 1998 research study. The Miller et. al. (2000) framework and definitions for segmented versus integrated project delivery will guide this comparison. Design-Bid-Build and DB PDMs are considered "segmented" delivery methods according to the Miller et. al. (2000) framework, and therefore, they are considered segmented delivery methods in this research. Similarly, the DBO

PDM is considered a combined or "integrated" delivery method and this definition will maintain consistency as well.

Research Methods and Research Question

In developing the methodology framework for this study, the following questions were first identified and answered:

1. What knowledge claims does the researcher make?
2. What strategies of inquiry will inform the procedures?
3. What methods of data collection and analysis will be used?

The first question implies that a researcher will begin a research project with specific assumptions about how and what they will learn during the process (Creswell, 2009). For this study, these assumptions were framed by previous research and further developed by a survey of the literature. It was assumed that a formal research methodology approach would lead to the in-depth learning of PDMs, project performance metrics, and statistical comparison methods. Secondly, the strategy that is used here is typically referred to as the "survey" strategy. Surveys are cross-sectional and longitudinal studies conducted by disseminating questionnaires or holding structured interviews for data collection purposes with the objective of making inferences about a research population from the generalizations of a sample (Creswell, 2009). Finally, the methods used for data collection and analysis will be survey distribution, statistical analysis, inference, and validation.

Together, the observed problem and theoretical point of departure framed the following research question for this study:

> "Does the measure of construction intensity have a direct correlation to the level of integration found within the Design-Bid-Build (DBB), Design-Build (DB), and Design-Build-Operate (DBO) project delivery methods (PDM) used to deliver water/wastewater infrastructure projects?"

Research Tasks

To facilitate a successful research study, the following research tasks were defined and completed:

- Define overarching research study objectives along with specific goals;
- Identify projects and project participants for data collection;
- Develop and disseminate a data collection instrument;
- Collect, sort, and clean collected project data;
- Statistically analyze the data;
- Discuss the results of the analysis; and
- Make inferences and apply the findings to the construction industry

Objectives and Specific Research Goals

The overarching objectives of this investigation were to: 1) determine if a correlation exists between CI and the level of integration inherent in the DBB, DB, and DBO PDMs for water/wastewater projects; and 2) apply the findings to the construction industry. The objectives serve as the overall vision for the research. In accomplishing these objectives, specific research goals were developed to dictate milestone achievements or data collection efforts, guiding the achievement of the vision. The specific research goals were to: 1) collect a minimum of 30 water/wastewater infrastructure projects, either current or past, for each of the three PDMs; 2) collect design and construction (D&C) duration and hard cost data for each project data point; 3) determine the level of integration for the DBB, DB, and DBO PDMs; and 4) classify these levels of integration utilizing the Miller et. al. (2000) delivery integration continuum.

Participant and Project Identification

The research questionnaire was circulated to key project participants including owners, project managers and project engineers, for both owners and contractors, to collect the data. These potential research participants were identified on the basis of their proximity to the project and knowledge of the industry. For this research, project managers, engineers, and utility owners were determined to fulfill this basis and were individually contacted by way of telephone or email to facilitate the data collection process.

Data Collection Instrument

The method used to gather the research data was the development and dissemination of a research questionnaire. The questionnaire was designed to be short, with only high-level project information being asked of each participant. The benefit of doing so was to limit the number of participants who would be deterred in providing this information as a result of an overwhelming or complicated questionnaire. The project information asked of participants included:

1. Project name and brief project description;
2. Project status;
3. Type of project;
4. Project location;
5. Delivery method used;
6. Number of years project has been in operations (if applicable);
7. Procurement strategy for primary contracting parties;
8. Form of contract used;
9. Initial or proposed design and construction duration; and
10. Project hard costs for design and construction

The full data collection instrument is attached in Appendix A. Because the identification of the PDM for each data point was considered critical to this study, question seven clarifies how the major contracting parties were procured. If the participant's delivery method identification provided did not match with the accepted definitions in question seven, a follow up clarification phone call or email message was sent. The following are the definitions used in question seven that were available for participant selection:

- "Design and Construction Contracted Separately. Owner will Operate and Maintain Facility"
- "Design and Construction Contracted Separately. Owner will Contract Another Party to Operate and Maintain the Facility"
- "Design and Construction Contracted with a Single Entity. Owner will Operate and Maintain Facility"
- "Design and Construction Contracted with a Single Entity. Owner Contracts with Another Party to Operate and Maintain Facility"
- "Design, Construction, Operations, and Maintenance Contracted with Single Entity for Specified Term"
- "Operations and Maintenance Contract for Long Term Operations and Maintenance of Facility Including Non-Capital Repairs"

Data Collection

The majority of the DBB and DB project data used in this research stems from the Bogus et. al. (2008) research study. The researchers involved in that study utilized a questionnaire to collect the data. The questionnaire was distributed to owners who were identified as having completed a water or wastewater project between 2003 and 2008 with a minimum cost of $3 million. The questionnaire for data collection was distributed in late June 2008 and included questions regarding:

- Respondent information;
- Project characteristics;
- Project delivery method;
- Schedule performance;
- Cost performance; and
- Quality performance.

In addition to this preexisting data, a handful of new DBB and DB project data points were added and used in this research.

All the DBO data collected was the result of an entirely different data collection effort tailored specifically to the objectives and goals of this research. The DBO data collection effort proved to be more difficult than anticipated. The initial approach for identifying projects and project participants consisted of Internet searches of DBO water/wastewater projects in the US. Those projects that were identified in this way were the larger and more current DBO projects. After obtaining the project names, the owner agency of these projects (primarily municipal water utilities) were identified and contacted by phone. In some instances, the data for these projects were collected over the phone during a brief 10-15 minute conversation. However, in the majority of instances, email addresses were exchanged during conversation and a follow up email with a questionnaire was sent to these contacts to fill out and send back. This approach proved effective for a limited number of project data points. When the fruits of this effort diminished, a new approach was taken.

The editor of Public Works Finance, William Reinhardt, was contacted over the course of the DBO data collection effort. The objective of this study was explained to Mr. Reinhardt as well as the difficulty encountered in collecting DBO data for the water/wastewater sector. He explained that the number of DBO water/wastewater projects currently underway in the US is severely limited, and offered his database as a starting point to generate additional project names and utility owners, of which, were individually contacted via phone or email. From here, the same process as above was utilized. This approach generated a significant amount of new project data, however, it did not generate over 30 data points, a specific goal of this study. As a result, a third and final approach was taken.

Four of the primary water/wastewater contractors and service providers in the US, known for entering into DBO contracts, were contacted by phone and email to obtain additional project data points. These entities included CH2M Hill's water/wastewater division, United Water, AECOM, and MWH. Because numerous DBO project data was requested of each company, a blank Microsoft Excel spreadsheet was created reflecting the questions in the formal data collection instrument. This was done to ease the burden on the project managers and engineers filling in the data for numerous projects simultaneously.

For every approach used, project fact sheets and contract agreements that could be easily located on the Internet were used to clarify and validate the information collected from the industry personnel. The questionnaires and fact sheets were stored electronically in project folders for each DBO project as well as in a Microsoft Excel spreadsheet.

The resources required to collect, store, clean, and organize the data included:

- Manpower
- Software

  - Microsoft Excel 2010 to store, organize, and clean the data
  - Microsoft Word 2010 to create the questionnaire
  - Microsoft Outlook 2010 to disseminate the questionnaire
- Phone to make contact with industry personnel and collect data in some instances

Overall, all the DBB, DB, and DBO data were combined together and used in the analysis. It should be noted that, in reality, all three data samples do not represent a truly random sample, but rather a sample by convenience. However, for the purposes of this study and data analysis, it will be *assumed* that all samples are random as this is an underlying assumption necessary to conduct any formal statistical analysis.

Data Analysis

Before conducting the statistical analysis, the data collected from research questionnaires, phone interviews, and project fact sheets were stored, organized, sorted, and cleaned using Microsoft Excel. The data was cleaned through the elimination of upper and lower outliers using a combination of quantitative and qualitative techniques. After cleaning the data, two statistical analyses software programs were used to conduct an ANOVA analysis on the three PDM data samples. The first was MVP stats and the second was SPSS, a data mining and statistical analysis program. An ANOVA was selected for data analysis, as it is the most appropriate method for comparing the variances and means of more than two data samples simultaneously. It is incorrect, in this case, to simply run three pairwise t-tests among the groups as doing so is inconsistent with the hypotheses stated and would increase the probability of committing a Type I Error, or rejecting a true null hypothesis (Luftig, 2011).

ANOVA analyses have the following advantages according to Luftig (2011):

- The researcher has maximum flexibility in terms of the number of treatment levels which may be tested, and the number of experimental units which may be assigned to each level;
- The design generally is not compromised in the event of lost or missing data (within reason);
- The analysis of the data resulting from this type of design is relatively straightforward.

The following are characters and definitions that were used in conducting the analysis:

- J = total number of groups or levels tested
- j = each of the J groups;
- n = number of observations in each of the j groups;
- i = each of the individual observations in each of the j groups

In general, an ANOVA analysis is an extension of the two-sample t-test for independent measures. In an ANOVA, the variance within a sample group is calculated as a combined estimate of the variance of the population (σ_w^2) and is referred to as the Mean Squares Within (S_W^2).

$$s_W^2 = \sum_{J=1}^{J} \frac{s_j^2}{J} = \frac{\sum_{J=1}^{J} \sum_{i=1}^{n} \left(x_{ij} - \overline{X_J}\right)^2}{J(n-1)} \qquad \text{Eq. (3.1)}$$

$$With\, J(n-1) = J_n - J\; df \qquad \text{Eq. (3.2)}$$

This value represents the unexplained variance, also referred to as residual variation, and is the denominator of the ANOVA test statistic. The other source of variation is the variability due to the differences of the means. The calculation for this variance is as follows and is the numerator in the ANOVA test statistic. It is referred to as the Mean Squares Between (S_B^2).

$$s_B^2 = n\sum_{J=1}^{J}\frac{(\overline{X_J} - \bar{X}_J)^2}{J-1}$$ Eq. (3.3)

$$With\,J - 1\ \ df$$ Eq. (3.4)

The ratio of Equation 1 to Equation 3 is equal to the test statistic for the analysis, which follows the F-distribution.

$$F = \frac{MS_B}{MS_W}$$ Eq. (3.5)

When the samples are from different populations with different means, the expected variance is:

$$\sigma_{means}^2 = \frac{\sigma_{within}^2}{n} + \sigma_{between}^2$$ Eq. (3.6)

Therefore, the expected variance of the means (the expected Mean Square) is equal to:

$$MS_B = \sigma_{within}^2 + n\sigma_{between}^2$$ Eq. (3.7)

Then, the expected ratio would be:

$$F = \frac{MS_B}{MS_W} = \frac{\sigma_{within}^2 + n\sigma_{between}^2}{\sigma_{within}^2}$$ Eq. (3.8)

From this equation, it is clear that if the variance between the groups is zero, F will equal unity. However, if there exists a difference among the group means, the expected F value will be greater than one. This is helpful in determining whether it is appropriate to accept or reject a null hypothesis.

The equations above present the methodology for conducting a traditional One Way ANOVA, also referred to as a Fischer ANOVA. However, in order to conduct a traditional ANOVA, the following assumptions must be met:

- Each of the underlying J data populations must be normally distributed;
- The variances of the J populations must be homogenous. This assumption may only be violated without significantly increasing the risk of error when the sample size (n) for each of the J groups is equal; and

- The observations reflect statistical independence, both within and between groups.

If any of these assumptions are violated in conducting the data analysis, variations of this traditional ANOVA must be used. For example, to test the differences in the dispersion of the data sets simultaneously when the data violate these assumptions, an Improved Levene Test, also known as the Brown-Forsythe Test, is the appropriate ANOVA technique. Similarly, to test the differences in the central tendency, a Welch test is the most appropriate. Strictly speaking, both are still One Way ANOVAs, but generate approximate F values instead of exact F values. These approximate F values were calculated by the MVP stats and SPSS statistician software for this research.

The data analysis utilized the following eight-step procedure for determining the shape, spread, and location comparisons of the sample sets, to ensure a comprehensive and accurate comparison. This procedure was developed by Luftig (2011) and is as follows:

1. State the underlying assumptions of the statistical test applied
2. State the null hypothesis
3. State the maximum risk willing to be accepted in committing a Type I (Alpha) Error
4. State the associated test statistic
5. Identify the Random Sampling Distribution (RSD) of the test statistic when the null hypothesis is true, and state whether it is an exact or approximate test
6. State the critical value(s) for rejecting the null hypothesis
7. Use MVP Stats or SPSS to perform the analysis calculations
8. Decide whether to accept or reject the null hypothesis. If the null hypothesis is rejected, provide an estimate for the descriptive statistic being tested

The details, procedure, and results of the data analysis are provided in Chapter four.

Conclusion

Overall, this chapter provided an outline of the methodology used to conduct the entirety of this research. It explained the overarching framework used and each individual piece contributing to the framework. Specifically, a problem and point of departure was identified as well as the data collection effort and research tasks that answer the research question. Because the statistical analysis used in this research is rigorous and robust, it is considered to be a self-validating study. However, it will be interesting to see if future research in this area, either quantitative or qualitative, derives similar findings.

CHAPTER IV

Data Analysis

Introduction

This chapter provides the details, procedure, and results of an ANOVA on the three collected data samples for DBB, DB, and DBO water/wastewater projects. It provides information regarding: 1) how the data sets were cleaned by removing outliers; 2) a description of the data sets themselves; 3) the research variables; 4) and an overview and detailed step-by-step procedure of the analysis. It concludes with a summary of the findings and information related to two additional analyses that were also conducted on variations of these three data samples, which can be found in Appendices B and C.

Cleaning the Data Sets

Although there is no formally established method for identifying and removing outliers from a data set, using the Interquartile Range (IQR) to identify both mild and extreme outliers is one of the most common quantitative techniques used and accepted by statisticians. Mild outliers commonly represent data points that fall above or below the value of 1.5 times the fourth spread of the data set, when this value is added to or subtracted from the median. Extreme outliers are considered those data points that fall above or below three times the fourth spread of the data set, when this value is added to or subtracted from the median. The IQR was able to accurately identify mild and extreme upper bound outliers but was not able to identify mild or extreme lower bound outliers, as the calculated lower bound was negative for each data set. Because construction projects do not have negative values for CI, a qualitative technique was used to identify lower bound outliers. It was determined that any project exhibiting a D&C capital cost below five million dollars would likely fall into the category of a retrofit project, and should not be considered in the data analysis. Including these small projects would significantly skew the results as it was assumed that the vast majority of retrofit projects, for any sector, are completed using the DBB PDM. Therefore, all CI values associated with project D&C capital costs below five million dollars were also removed. This is similar to the Bogus et. al. 2008 study where all projects under three million dollars were removed from the data set. It is appropriate to use a slightly higher cut-off point in this research since DBO projects are being considered and the majority of these projects exhibit larger capital costs over their DBB and DB counterparts. Overall, each data set was reduced to the following during the cleaning process:

- DBB sample was reduced from 73 to 44 data points;
- DB sample was reduced from 33 to 28 data points; and
- DBO sample was reduced from 38 to 34 data points for a total of 106 data points total

Describing the Data Sets

Every project used as a data point was, or is currently being executed in the US. Figure 4.1 represents maps of all the states represented by the data in each of the three PDM samples. The DBB, DB, and DBO project data are represented by the orange, red, and green states respectively.

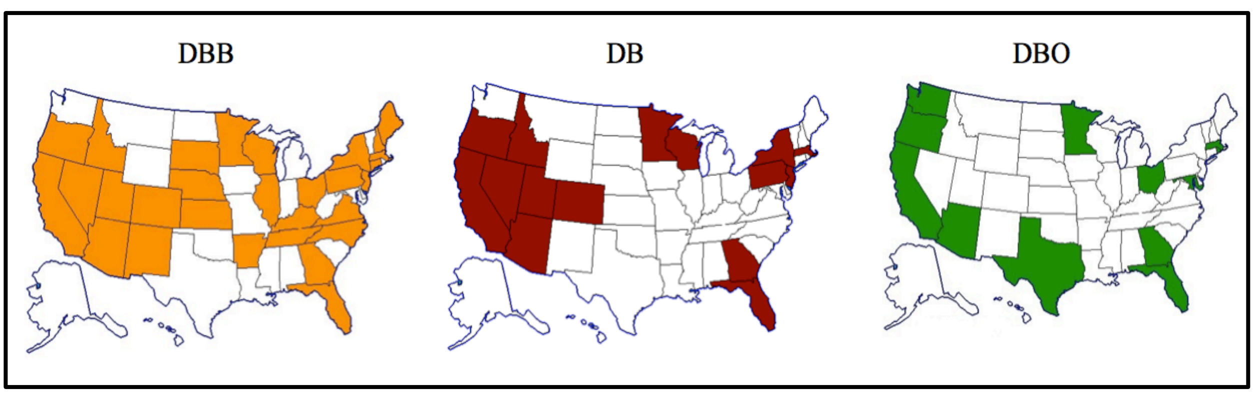

Figure 4.1: Project Data Locations

The DBB PDM represents 28 of the fifty United States. This is substantially more than the 16 states represented by DB projects and the 12 represented by DBO projects. This is indicative of what was found in the literature survey as all states allow the use of DBB delivery, while a limited number allow DB and/or DBO delivery.

Table 4.1 presents information regarding the dates the projects entered into operations.

Table 4.1: Operations Date Data

Date Operations Began				
	DBB	**DB**	**DBO**	**Units**
Mean	2007	2006	2006	-
Median	2008	2006	2006	-
Mode	2008	2007	2000	-
Range	44	7	23	Years
Std. Dev.	4.74	1.71	4.88	Years
High	2014	2010	2014	-
Low	1970	2003	1991	-

It was assumed that shortly after a project reached substantial completion, it would enter into operations. Subtracting the design and construction duration from the operations year yielded an estimate for the commencement date of each project. This estimate was then used to normalize the cost data across all three samples. From the table, it is apparent that the majority of projects, for all data sets, entered into operations around 2006 and 2007.

Table 4.2 reveals the D&C duration data for each sample set.

Table 4.2: Design and Construction Duration Data

Design and Construction Duration (Months)			
	DBB	**DB**	**DBO**
Data Pts.	44	28	34
Mean	38	21	26
Median	36	18	26
Mode	36	-	24
Range	84	43	31
Std. Dev.	18	11	7
High	96	48	42
Low	12	5	11

From the table, DBB projects are shown to have, on average, a 63% longer D&C schedule duration than their DB and DBO counterparts. Additionally, there is not a single DBB project in the cleaned data set that was completed in less than one year. Furthermore, the largest D&C duration value is found in a DBB project. DB projects showed the lowest average for duration values across all three data sets, even though the range of duration data is similar for DB and DBO project samples. This may be due to larger projects being constructed using the DBO PDM than the DB PDM since both methods overlap D&C phases, compressing the project schedule, in a similar manner.

Table 4.3 presents the D&C hard cost data used in the study, and Figure 4.2 is a graph representing the D&C capital cost data for all three sample sets.

Table 4.3: Design and Construction Hard Cost Data

Design and Construction Hard Cost (2010 Dollars)			
	DBB	DB	DBO
Data Pts.	44	28	34
Average	$25,000,000	$36,000,000	$68,000,000
Median	$14,000,000	$16,000,000	$41,000,000
Mode	-	-	-
Range	$120,000,000	$140,000,000	$240,000,000
Std. Dev.	$26,000,000	$42,000,000	$60,000,000
High	$120,000,000	$150,000,000	$240,000,000
Low	$5,100,000	$5,700,000	$7,400,000

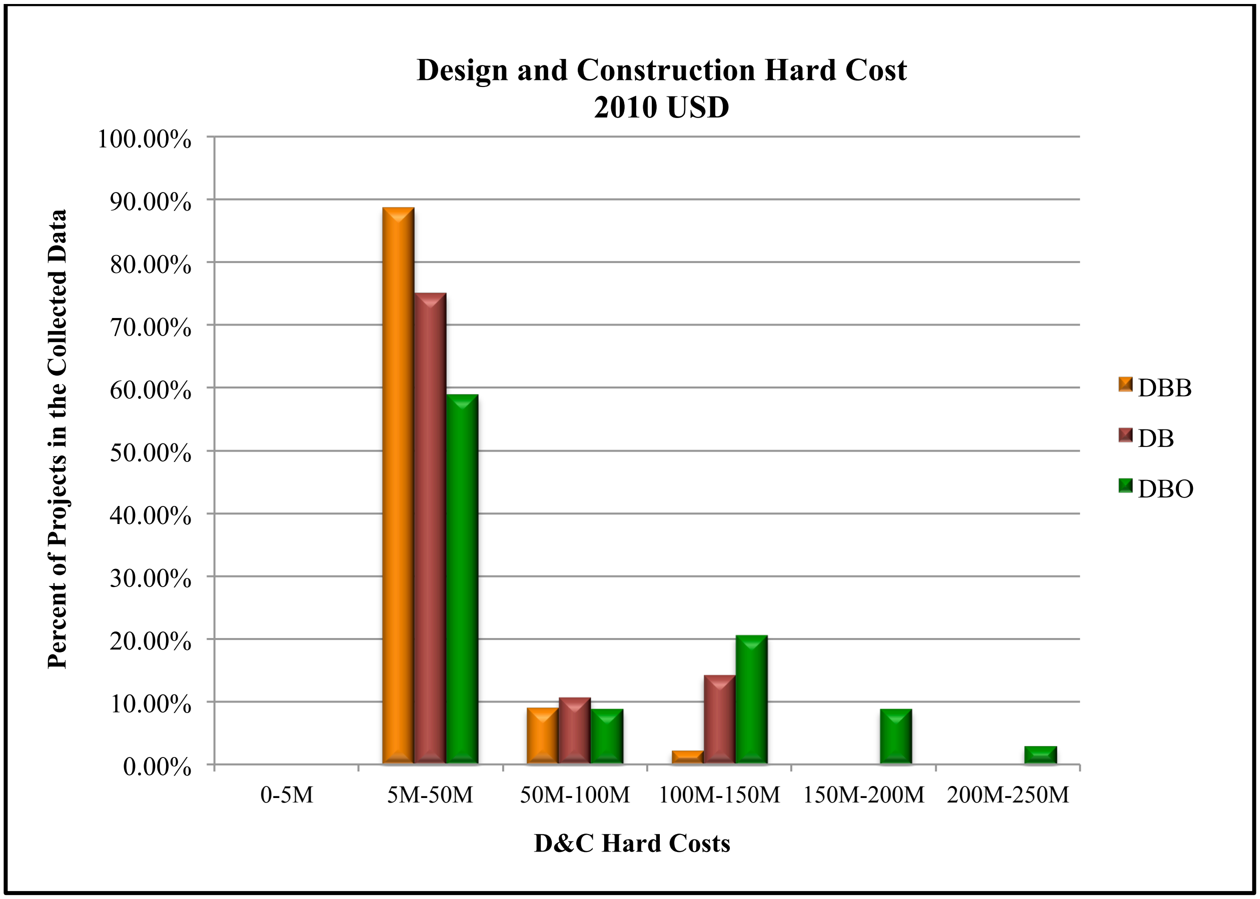

Figure 4.2: Design and Construction Hard Cost Data

In order to make the data sets comparable, all D&C hard cost values were converted to 2010 present values using Engineering News Record's (ENR) Construction Cost Indices (CCI). The CIIs are updated each month and account for the materials and labor used in the industry (ENR, 2011). To normalize the cost data, the annual CCI values were used in the following manner:

$$D\&C\ Hard\ Costs\ (2010\ USD) = \frac{D\&C\ Hard\ Cost}{CCI\ (Design\ Year)} * CCI\ (Year\ 2010) \qquad \text{Eq. (4.1)}$$

All D&C cost data was normalized utilizing the year design began. Table 4.3 and Figure 4.2 reveal that, on average, the capital costs for the DBO data is 272% higher than that for DBB projects. Additionally, DB projects, on average, exhibit higher hard costs for D&C than did DBB by 144%.

Table 4.4 presents the CI data for each PDM, and Figure 4.3 is a scatter plot graph of CI for all three data samples.

Table 4.4: Construction Intensity Data

Design and Construction Intensity (2010$/Mo.)			
	DBB	DB	DBO
Data Pts.	44	28	34
Average	$520,000	$1,100,000	$2,300,000
Median	$450,000	$880,000	$1,400,000
Mode	-	-	-
Range	$1,200,000	$2,100,000	$6,400,000
Std. Dev.	$340,000	$680,000	$1,800,000
High	$1,300,000	$2,400,000	$6,800,000
Low	$100,000	$310,000	$410,000

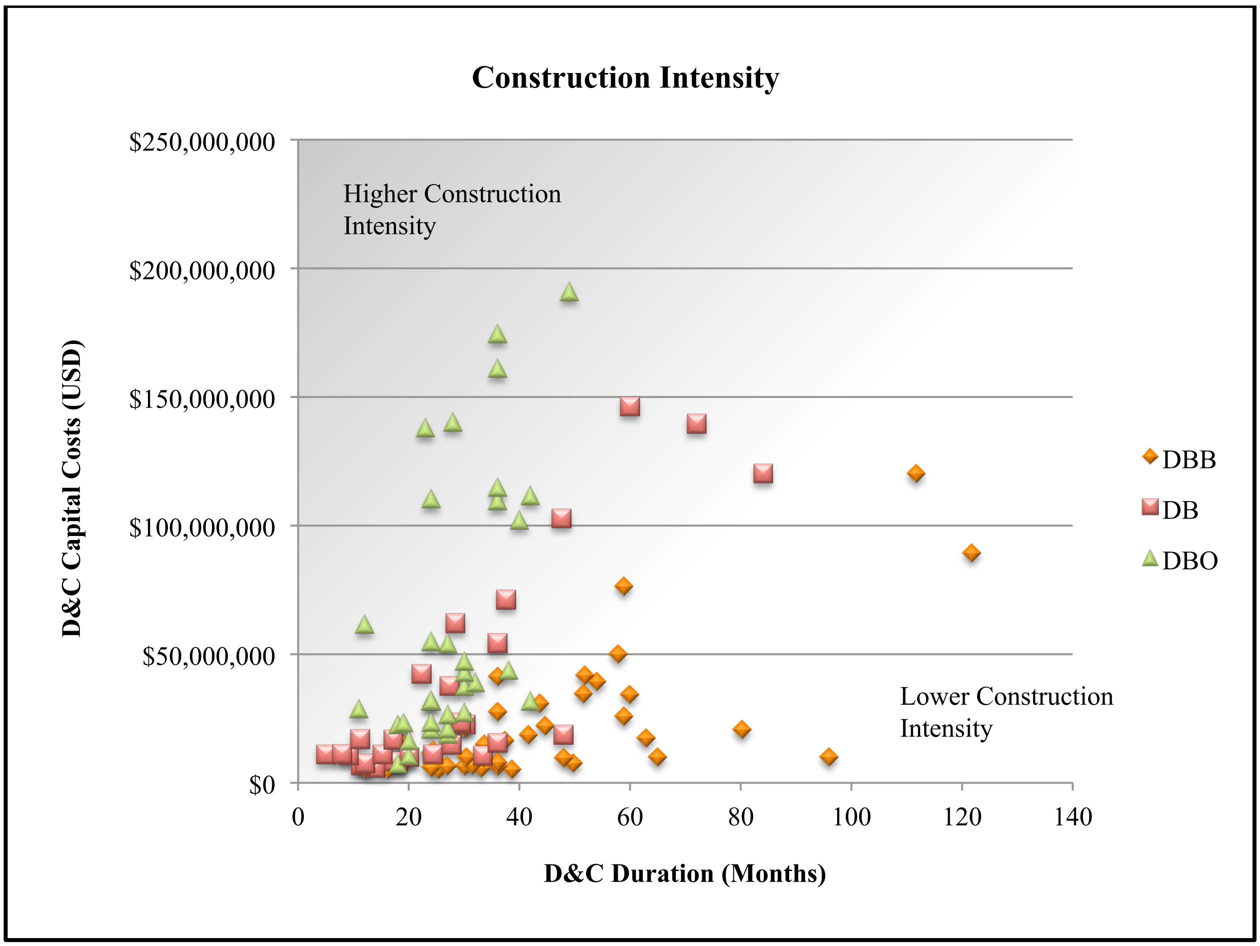

Figure 4.3: Construction Intensity Data

Overall, DBO projects exhibit a greater degree of CI, on average, over its DB and DBB counterparts. This difference in degree is significant and nearly 442% greater when compared to DBB and 210% greater when compared to DB. Moreover, DB also exhibits a significantly greater degree of CI over DBB by nearly 210%. The medians of each data represent similar rankings as the averages. The DBO median for CI is 160% greater than then median for DB projects, and 311% greater than the median for DBB projects.

Research Variables

The measurable variables for this investigation were both quantitative and qualitative. The quantitative parameters were: 1) D&C duration quantified by months; and 2) D&C hard costs normalized to 2010 USD. The degree of delivery integration represented the qualitative variable. Previous research by John B. Miller and the ISDR at MIT group coded PDMs using this degree as a parameter of classification. The findings from these research efforts were considered comprehensive, and therefore, were applied here.

The dependent research variable for this research was CI. The criterion measure for CI was D&C hard costs per D&C duration. The CI variable was considered underlying continuous, ratio data. Conversely, the independent research variable was the PDM level of integration classified by Miller et. al. (2000). This variable was measured quantitatively and was considered nominal data.

Table 4.5 present the descriptive statistics for the three PDM data samples.

Table 4.5: Descriptive Statistics for the Data Samples

Descriptive Statistics						
PDM	**N**	**Mean**	**Std. Dev.**	**Low**	**High**	**Range**
(All)	106	7.0E+05	9.7E+05	9.5E+04	5.1E+05	8.8E+05
DBB	44	2.6E+05	2.3E+05	3.4E+04	1.9E+05	3.3E+05
DB	28	5.9E+05	4.0E+05	7.6E+04	4.4E+05	7.5E+05
DBO	34	1.3E+06	1.5E+06	2.5E+05	8.3E+05	1.8E+06

Overview and Statistical Hypotheses

In order to answer the research question, the following statistical hypotheses were tested and answered in the following order:

Shape: Test for Normality (Moment Tests)

$H_0: \gamma 3 = 0.00 \qquad H_1: \gamma 3 \neq 0.00$

$H_0: \gamma 4 = 0.00 \qquad H_1: \gamma 4 \neq 0.00$

It is important to note that normality will be tested for the project data within each of the three PDM data sets individually, not in aggregate.

Spread: Test for the Dispersion of the Means

$H_0: \sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$

$H_1: \sigma^2_{DBB} \neq \sigma^2_{DB} \neq \sigma^2_{DBO}$

Location: Test for the Equality of Means

$H_0: \mu_{DBB} = \mu_{DB} = \mu_{DBO}$

$H_1: \mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$

Determining the Underlying Shape of the Research Population: Testing for Normality

When sample sizes contain less than 25 data points, the appropriate test for normality is the Anderson-Darling Test. In contrast, when sample sizes are greater than 25, the appropriate tests for normality are the moment tests in which skewness and kurtosis are tested separately. In this study, all sample sizes for each of the examined PDMs are greater than 25, and therefore, the moment tests were used. The following eight-step procedure was utilized for all three data sets simultaneously in testing for normality, as the results and procedure itself were similar for each.

Eight-Step Statistical Hypothesis Test Procedure for Normality

1. Underlying Assumptions of the Test For Normality:
    a. The data are continuous
    b. The data was randomly drawn from a process/population

       *Note: In this case, the data is not a truly random sample, but rather a sample by convenience.
2. The Test Hypotheses:

$$H_0: \gamma_3 = 0.00 \qquad H_1: \gamma_3 \neq 0.00$$

$$H_0: \gamma_4 = 0.00 \qquad H_1: \gamma_4 \neq 0.00$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:
    a. For The Moment Tests:
        i. Skewness—t-statistic
        ii. Kurtosis—standard table values for kurtosis
5. Random Sampling Distribution of the Test Statistic when H_0 is True:
    a. For moment tests
        i. Skewness—t-statistic (Approximate)
        ii. Kurtosis—simulated or normal (Approximate)
6. The Critical Value for Rejecting the Null Hypothesis:

$$\text{Reject } H_0 \text{ if p-value} < 0.05$$

7. Calculations:

The calculations for normality were computed using the MVP stats software. The results of these computations are presented below in Table 4.6. The yellow highlights denote p-values outside of the stated level of risk acceptance.

Table 4.6: Testing for Normality

Normality Tests									
PDM	N	Mean	Variance	Skewness	p-value	Kurtosis	p-value	W(E)	p-value
(All)	106	1.3E+06	1.7E+12	2	0.000*	4.90	<0.02*	0.01	0.0069*
DBB	44	5.2E+05	1.2E+11	1.0	0.011*	0.20	>.10	0.04	0.0134*
DB	28	1.1E+06	4.7E+11	1	0.249	-1.20	>.10	0.05	0.0203*
DBO	34	2.3E+06	3.1E+12	1.0	0.014*	-0.04	>.10	0.04	0.0173*

8. Decide whether to accept or reject H_0:

   a. Decisions:

      i. Reject H_0 for DBB data set

      ii. Accept H_0 for DB data set

      iii. Reject H_0 for DBO data set

   b. P-values (Asterisks represent p-values below the acceptable 0.05 level):

      i. P values for DBB data set: $\approx$ 0.011* and >0.10

      ii. P value for DB data set: $\approx$ 0.249 and >0.10

      iii. P value for DBO data set: $\approx$ 0.014* and >0.010

   c. There exists sufficient statistical evidence to infer that the DBB and DBO sample data sets are not normally distributed. Therefore, the underlying research population can also be inferred to not follow a normal distribution for these PDMs. However, there exists sufficient statistical evidence to infer that the DB sample set is normally distributed. Therefore, the underlying research population data can also be inferred to follow a normal distribution for the DB PDM.

d. Estimate of shape: Using the MVP stats histogram generation program, the distributions found to best fit all three data sets were as follows:

i. Gamma (0) distribution for DBB data with a fit of 0.987

ii. Gamma (0) distribution for the DBO data set with a fit of 0.958

From the normality tests, it is clear that two of the data sets are *not* normally distributed and the number of data points in each set is not equal. Because of this, a traditional Fischer One Way ANOVA is not applicable. Therefore, Leven's Improved Test (Brown-Forsythe Test) for Dispersion, and a Welch test for central tendency were used.

Levene's Improved Test (Brown-Forsythe Test) for Dispersion

In order to conduct a Levene's improved test for dispersion on data that is not normally distributed and between sample sets of unequal size n, the Absolute Deviations from the Median (ADMs) for all three groups must first be computed. Doing so has been shown to significantly increase the effectiveness of the test (Luftig, 2011). These absolute values can then be compared using an ANOVA. The ADMs were found utilizing the MVP stats software. After calculating the ADMs, these data were transferred into SPSS to conduct the comparison analysis. The descriptive statistics for each PDM are presented in Table 4.7.

Table 4.7: Dispersion Descriptive Statistics for CI

Dispersion ADM Descriptive Statistics (CI)								
	N	Mean	Std. Dev.	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Minimum	Maximum
DBB	44	2.6E+05	2.3E+05	3.4E+04	1.9E+05	3.3E+05	1.2E+03	9.0E+05
DB	28	5.9E+05	4.0E+05	7.6E+04	4.4E+05	7.5E+05	8.5E+04	1.6E+06
DBO	34	1.3E+06	1.5E+06	2.5E+05	8.3E+05	1.8E+06	4.9E+04	5.4E+06
Total	106	7.0E+05	9.7E+05	9.5E+04	5.1E+05	8.8E+05	1.2E+03	5.4E+06

Eight-Step Test Procedure

1. Underlying Assumptions for Levene's Improved Test for Dispersion:
    a. The data are continuous
    b. The data was randomly drawn from a process/population

       *In this case, the data is not a truly random sample, but rather a sample by convenience.
    c. The underlying data is *not* normally distributed
    d. The data sets compared are of *unequal* size n
2. The Test Hypotheses:

$$H_0: \sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$$

$$H_1: \sigma^2_{DBB} \neq \sigma^2_{DB} \neq \sigma^2_{DBO}$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:
    a. F-test statistic
5. Random Sampling Distribution of the Test Statistic when H_0 is True:
    a. The F-statistic RSD (approximate value and calculated using MVP Stats, shown as Figure 4.4) when $p = 0.05$, with $J - 1$ and $n_{total} - J$ degrees of freedom (df) where:
        i. $J = 3$, and
        ii. n_{total} equals the total number of DBB, DB, and DBO data points

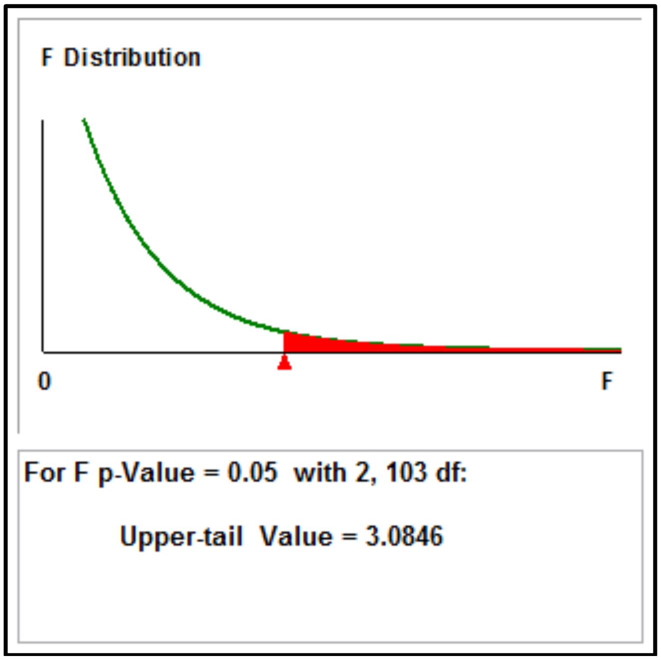

Figure 4.4: F-Statistic Approximate RSD (Generated Using MVP Stats)

6. The Critical Value for Rejecting the Null Hypothesis:

Reject H_0 if $F > 3.0846$ and/or P-value < 0.05

7. Calculations:

The calculations for dispersion were done utilizing both MVP stats to generate the ADMs and SPSS to perform the ANOVA. The results of the Brown-Forsythe ANOVA test are presented in Table 4.8.

Table 4.8: Robust Test of Equality for Dispersion

Robust Tests of Equality of Means (CI ADMs)				
	Statistic*	df1	df2	Sig.
Welch	16	2	48	0.00
Brown-Forsythe	14	2	40	0.00

*Asymptotically F-Distributed

8. Decide whether to accept or reject H_0:

    a. Decisions:

        i. Reject H_0

b. F and P-values for the Brown-Forsythe Test:

i. $F = 14^* > 3.0846$

ii. $P = 0.00^* < 0.05$

c. There exists sufficient statistical evidence to infer that:

$$\sigma^2_{DBB} \neq \sigma^2_{DB} \neq \sigma^2_{DBO}$$

Although the null hypothesis was rejected, this does not undoubtedly conclude that a significant difference occurs between *all* three PDM means. In fact, the null hypothesis can be rejected in instances where there exists a large difference between only two of the three data samples. To further determine the characteristics of this significant difference, a Post-Hoc analysis was warranted. The results of this analysis are presented below in Table 4.9 to individually compare and assess the differences in the CI dispersion value means.

Table 4.9: Post-Hoc Analysis of Variance (Generated Using SPSS)

Games-Howell Multiple Comparisons (ADMs of CI)						
(I) PDM	(J) PDM	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
DBB	DB	-3.3E+05	8.4E+04	0.001	-5.4E+05	-1.3E+05
	DBO	-1.1E+06	2.5E+05	0.000	-1.7E+06	-4.6E+05
DB	DBB	3.3E+05	8.4E+04	0.001	1.3E+05	5.4E+05
	DBO	-7.5E+05	2.6E+05	0.018	-1.4E+06	-1.1E+05
DBO	DBB	1.1E+06	2.5E+05	0.000	4.6E+05	1.7E+06
	DB	7.5E+05	2.6E+05	0.018	1.1E+05	1.4E+06

The results of this comparison reveal that the differences between all three PDMs were significant and fall below the 0.05 significance level defined for this research. Therefore, it is the mean differences between all three samples that drive the rejection of the null hypothesis. Figure 4.5 reveals how the ADMs of each PDM's CI values compare to one another and further confirms the findings in Table 4.9.

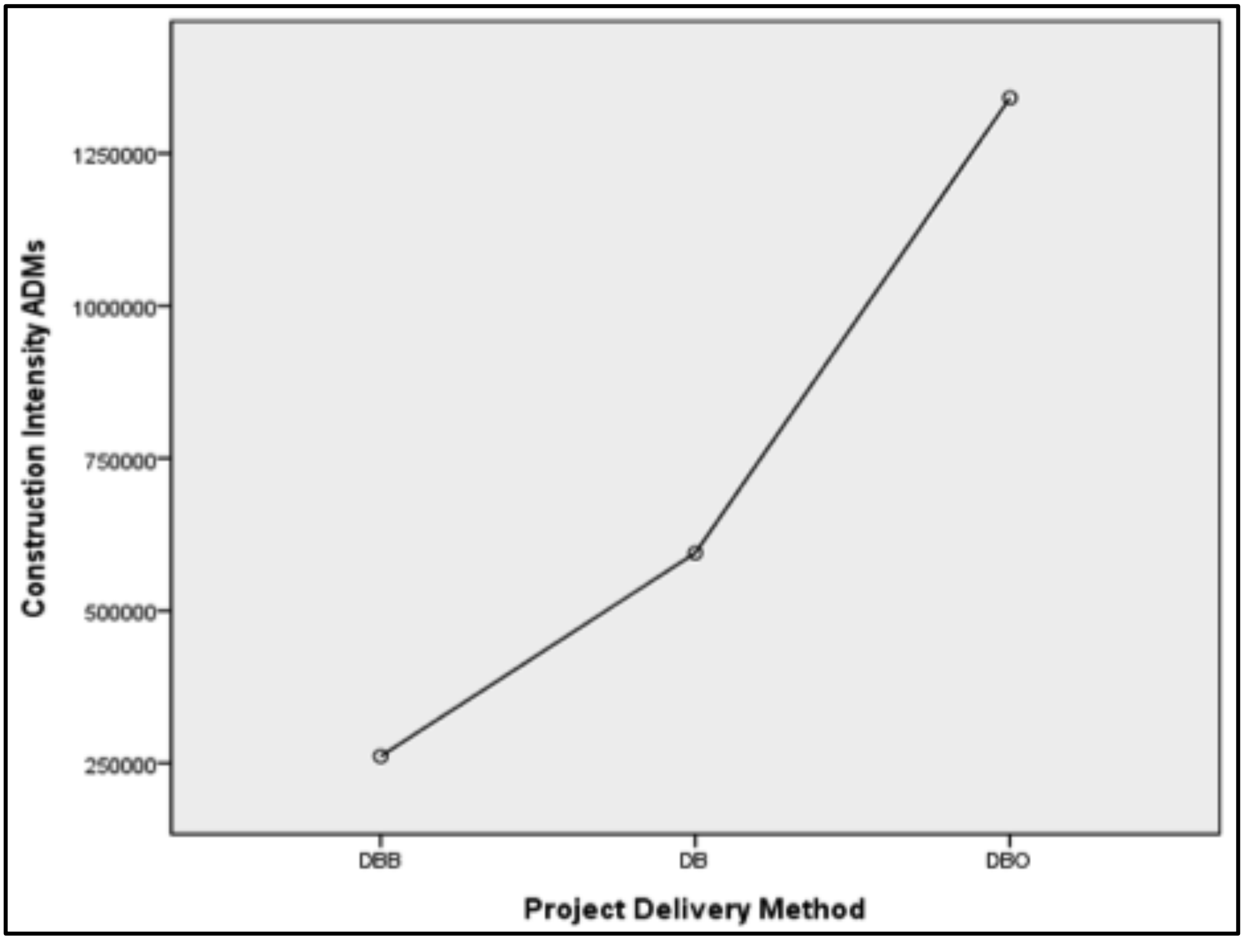

Figure 4.5: Mean of the CI ADMs (Generated Using SPSS)

From the Post Hoc analysis and graph, it is clear that:

$$\sigma^2_{DBB} < \sigma^2_{DB} < \sigma^2_{DBO}$$

Because the null hypothesis was rejected, it is necessary to provide an estimate for the variability of each sample set. This is done in the "Summary and Results" section at the end of this analysis chapter.

One Way Robust ANOVA for Central Tendency

The descriptive statistics for each PDM sample in conducting a One Way Robust ANOVA for central tendency are presented in Table 4.10.

Table 4.10: Central Tendency Descriptive Statistics for CI

Central Tendency Descriptive Statistics (CI)								
	N	Mean	Std. Dev.	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Minimum	Maximum
DBB	44	5.2E+05	3.4E+05	5.1E+04	4.1E+05	6.2E+05	1.0E+05	1.3E+06
DB	28	1.1E+06	6.8E+05	1.3E+05	8.6E+05	1.4E+06	3.1E+05	2.4E+06
DBO	34	2.3E+06	1.8E+06	3.0E+05	1.7E+06	2.9E+06	4.1E+05	6.8E+06
Total	106	1.3E+06	1.3E+06	1.3E+05	1.0E+06	1.5E+06	1.0E+05	6.8E+06

Eight-Step Test Procedure

1. Underlying Assumptions for One Way Robust ANOVA for Central Tendency:
    a. The data are continuous
    b. The data was randomly drawn from a process/population

       *In this case, the data is not a truly random sample, but rather a sample by convenience.
    c. The underlying data is *not* normally distributed
    d. The data sets compared are of *unequal* size n
2. The Test Hypotheses:

$$H_0: \mu_{DBB} = \mu_{DB} = \mu_{DBO}$$

$$H_1: \mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:
    a. F-test statistic
5. Random Sampling Distribution of the Test Statistic when H_0 is True:
    d. The F RSD (approximate and calculated using MVP Stats, shown as Figure 4.6) when $p = 0.05$, with $J - 1$ and $n_{total} - J$ degrees of freedom (df) where:
        i. $J = 3$, and

ii. n_{total} equals the total number of DBB, DB, and DBO data points

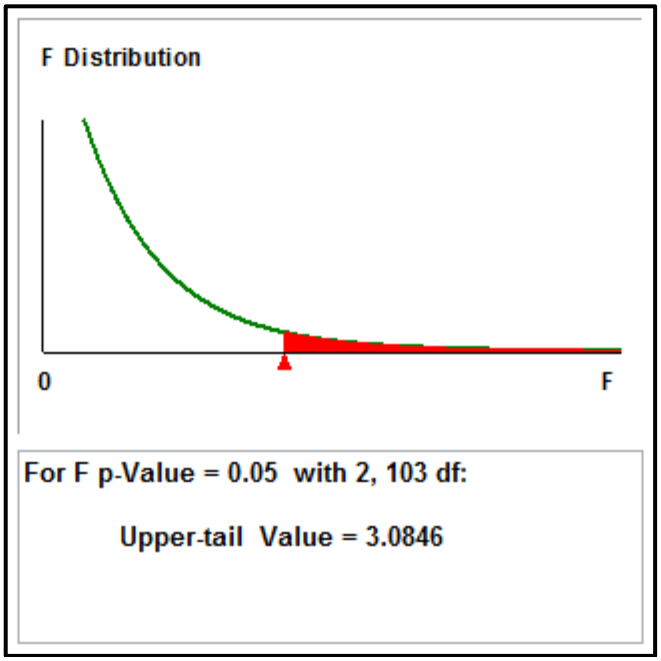

Figure 4.6: F-Statistic Approximate RSD (Generated Using MVP Stats)

6. The Critical Value for Rejecting the Null Hypothesis:

Reject H_0 if $F > 3.0846$ and/or P-value < 0.05

7. Calculations:

The calculations for the One Way ANOVA of central tendency were done utilizing SPSS. The results of both a Welch and Brown-Forsythe ANOVA test are presented in Table 4.11. Because the Welch test is generally more conservative in comparing central tendency, the results for this test were used in the analysis.

Table 4.11: Robust Tests for Equality of Means

Robust Tests of Equality of Means (CI)				
	Statistic*	df1	df2	Sig.
Welch	25	2	47	0.000
Brown-Forsythe	25	2	46	0.000
*Asymptotically F-Distributed				

8. Decide whether to accept or reject H_0:

    a. Decisions:

        i. Reject H_0

    b. F and P-values for the Welch Test:

        i. F = 25* > 3.0846

        ii. P = 0.000* < 0.05

    c. There exists sufficient statistical evidence to infer that:

$$\mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$$

Although the null hypothesis has been rejected, this does not automatically conclude that a significant difference occurs between *all* three PDM means. In fact, the null hypothesis can be rejected in instances where there exists a large difference between only two of the three data sets. To further determine the characteristics of this significant difference, a Post-Hoc analysis is warranted. The results of this analysis are presented below in Table 4.12 to individually compare and assess how the differences of each PDM's mean CI values compare to one another.

Table 4.12: Post-Hoc Analysis of Central Tendency (Generated Using SPSS)

Games Howell Multiple Comparisons (CI)						
(I) PDM	(J) PDM	Mean Diff. (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
DBB	DB	-6.0E+05	1.4E+05	0.000	-9.4E+05	-2.6E+05
	DBO	-1.8E+06	3.1E+05	0.000	-2.5E+06	-1.0E+06
DB	DBB	6.0E+05	1.4E+05	0.000	2.6E+05	9.4E+05
	DBO	-1.2E+06	3.3E+05	0.002	-2.0E+06	-3.9E+05
DBO	DBB	1.8E+06	3.1E+05	0.000	1.0E+06	2.5E+06
	DB	1.2E+06	3.3E+05	0.002	3.9E+05	2.0E+06

The results of this comparison reveal that the differences between all three PDM sample sets are significant. Therefore, it is the mean differences between DBB, DB, and DBO CI values that drive the rejection of the null hypothesis. Figure 4.7 below is a graph revealing how the mean CI values of each PDM sample set compare to one another.

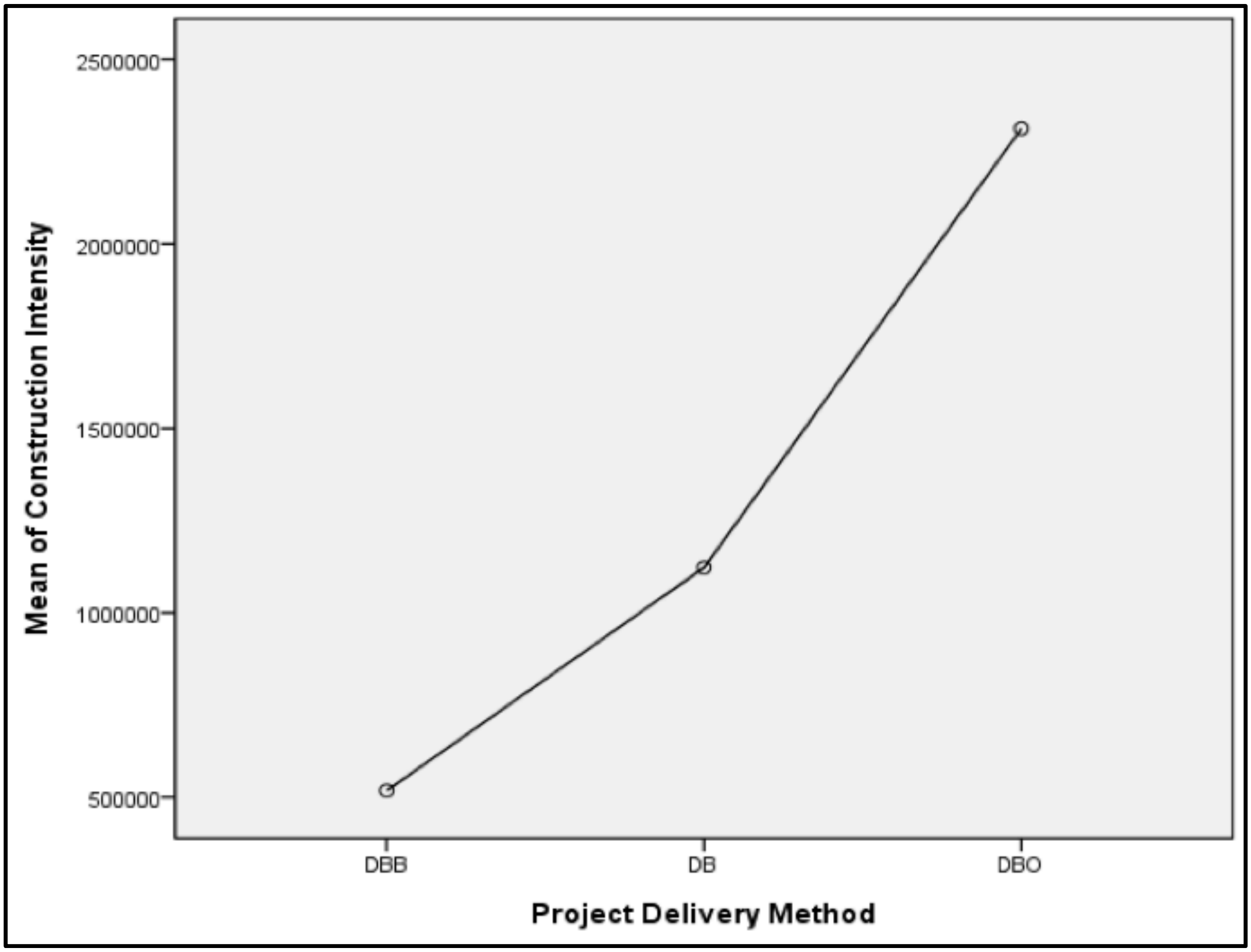

Figure 4.7: Mean of CI Values (Generated Using SPSS)

From the Post Hoc analysis and graph, it is clear that:

$$\mu_{DBB} < \mu_{DB} < \mu_{DBO}$$

Summary and Results

In conducting the analysis, it was determined that only the DB PDM sample set was normally distributed. Therefore, statistically speaking, it can be inferred that the underlying research population for the DBB and DBO data sets are not normally distributed while the underlying research population for the DB project data appear to be. However, in reality, it is highly unlikely that any of the underlying research populations are truly normally distributed as the nature of the construction industry promotes highly unique projects. Finding the DB data set to have a somewhat normal distribution is likely the result of sampling by convenience rather than using a truly random sample in the analysis. As a result of two of the three data sets revealing non-normal behavior and the unequal sizes of the samples, a traditional Fischer ANOVA could not be conducted. Instead, an improved Levene test for dispersion and Welch test for central tendency were used. The finding for the ANOVA of dispersion was that the variability of DBO projects, in regards to CiI, is greater than DB projects, which, in turn, is greater than DBB projects. Because of this, the null hypothesis was rejected and Figures 4.8, 4.9, and 4.10 reveal estimates for the actual variability of the data sets followed by an estimate for natural tolerance (NT).

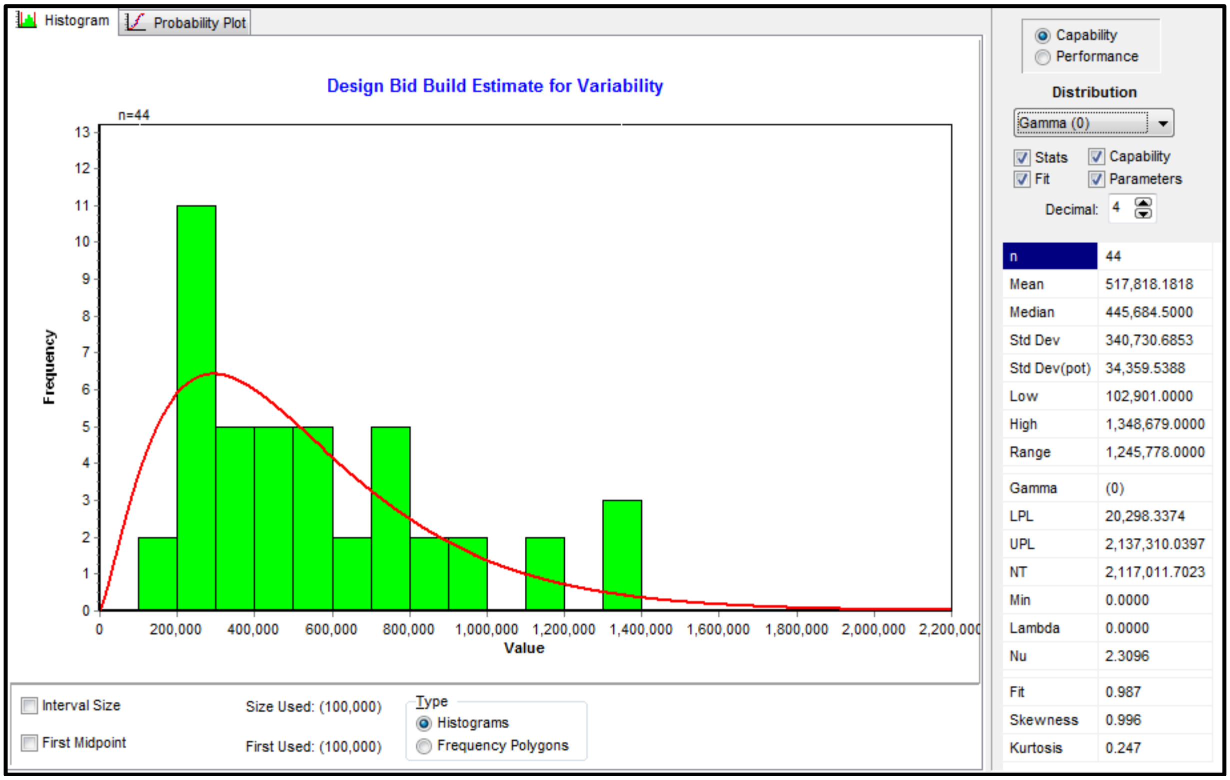

Figure 4.8: DBB Estimate of Variability (Generated Using MVP Stats)

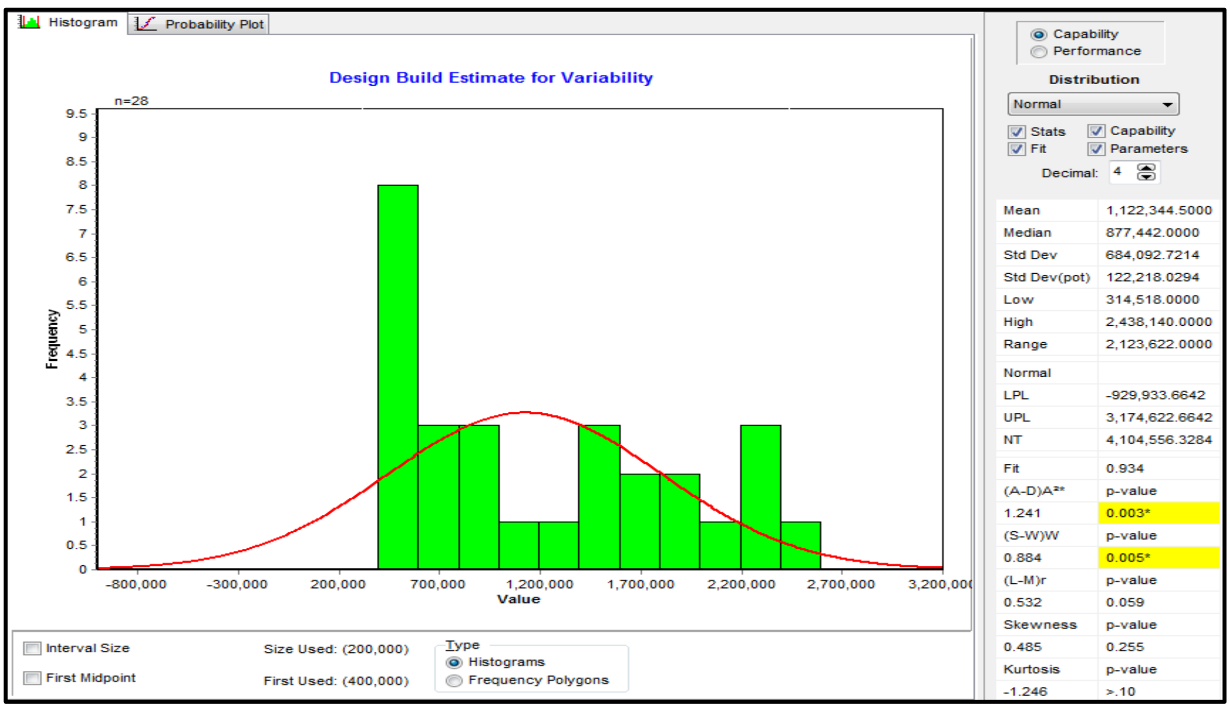

Figure 4.9: DB Estimate of Variability (Generated Using MVP Stats)

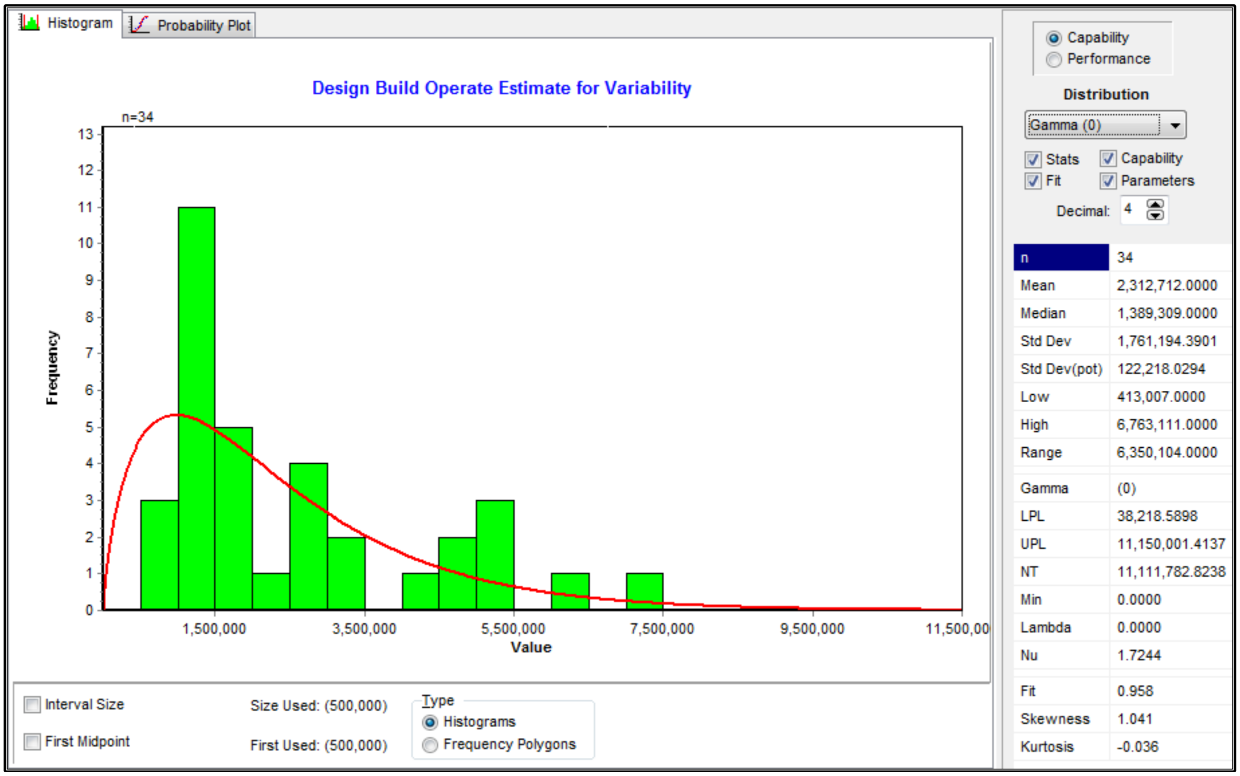

Figure 4.10: DBO Estimate of Variability (Generated Using MVP Stats)

Estimate of Natural Tolerance for DBB, DB and DBO Variability:

$$NT_{DBB} = 2{,}100{,}000$$

$$NT_{DB} = 4{,}100{,}000$$

$$NT_{DBO} = 11{,}000{,}000$$

The results of the Welch ANOVA analysis of central tendency were that the means of CI for DBB is statistically less than that of DB, which is less than that of DBO. Because of this, the null hypothesis was rejected and estimates for the means of the data sets are as follows:

$$\mu_{est\ DBB} = \$520{,}000/Month$$

$$\mu_{est\ DB} = \$1{,}100{,}000/Month$$

$$\mu_{est\ DBO} = \$2{,}300{,}000/Month$$

Calculating Importance:

When an ANOVA reveals that a statistically significant difference exists between data samples, this implies that the observed difference(s) are likely not a result of sampling error but, instead are a result of a true difference in the population parameters tested. However, this does not imply that this difference is statistically *important*. Therefore, a calculation of statistical importance is warranted. In this study, a statistically significant difference between CI means was determined to be most meaningful, and therefore, a calculation of statistical importance will be conducted for central tendency only. The equation for statistical importance (ω^2) is presented below:

$$\omega^2 = \frac{(J-1)(F-1)}{(J-1)(F-1)+J_n} \qquad \text{Eq. (4.2)}$$

The following breakdown is helpful as a generalization associated with Fixed Effect ANOVAs for evaluating the importance of the statistical findings when comparing continuous data sets according to Luftig (2011):

- 70% – 100% ~ Very Important
- 50% – 69% ~ Moderate Importance
- 25% – 49% ~ Low Importance
- < 25%~ Unimportant

Using the more conservative Welch Test F-Value in calculating importance:

$$\omega_\mu^2 = \frac{(3-1)(25-1)}{(3-1)(25-1)+[(44+28+34)/3]}$$

$$\omega_\mu^2 = \frac{(2)(24)}{(2)(24)+(35.33)}$$

$$\omega_\mu^2 = \frac{48}{83.33}$$

$$\omega_{\mu}^{2} = 57.6\%$$

Overall, an ANOVA of the CI values for each of the three PDMs has revealed that there is a statistically significant and moderately important difference in the means of these values for DBB, DB, and DBO delivery. The mean CI of DBO is much higher than DBB, and DB at $2,300,000/month. The mean CI for DB is higher than DBB, but lower than DBO at a value of $1,100,000/month. Finally, the mean CI for DBB is the lowest at $520,000/month.

CHAPTER V

Application and Conclusion

Summary of the Results

Three different statistical data analyses of the data have confirmed the intuition that was stated as part of the research methodology. The first was conducted on a clean data set in which upper and lower bound mild and extreme outliers were removed using a mixture of quantitative and qualitative techniques in an application that made sense for data rooted in the construction industry. This analysis was presented in Chapter IV. The second analysis involved all the data points collected for this study in their entirety. The full analysis is presented in Appendix B. Finally, the third analysis involved only PDM data that corresponded to a hard cost range from five million to 50 million dollars with the belief that limiting the data to this range would allow each PDM's ability to compress project schedules determine the degree of CI rather than hard costs. The full analysis for this data is presented in Appendix C.

Overall, all three analyses revealed similar findings regarding the central tendency comparisons between data samples. In each analysis, DBO projects were found to display a statistically significant and greater degree of CI when compared to DBB and DB projects. Moreover, two of the three analyses showed that the mean of CI values for DB projects was significantly greater than DBB project CI values. The analysis that included all data points was the only analysis that showed DBB and DB CI means to be statistically equal. However, this statistical equality was well under the value of unity, at 0.54 as shown in the Post-Hoc analysis, with DB data representing a higher mean for CI. The overwhelming result of all three analyses was that a more integrated PDM was shown to exhibit a higher degree of CI. The results from the analysis in chapter four, on the cleaned data set, is provided graphically in Figure 5.1.

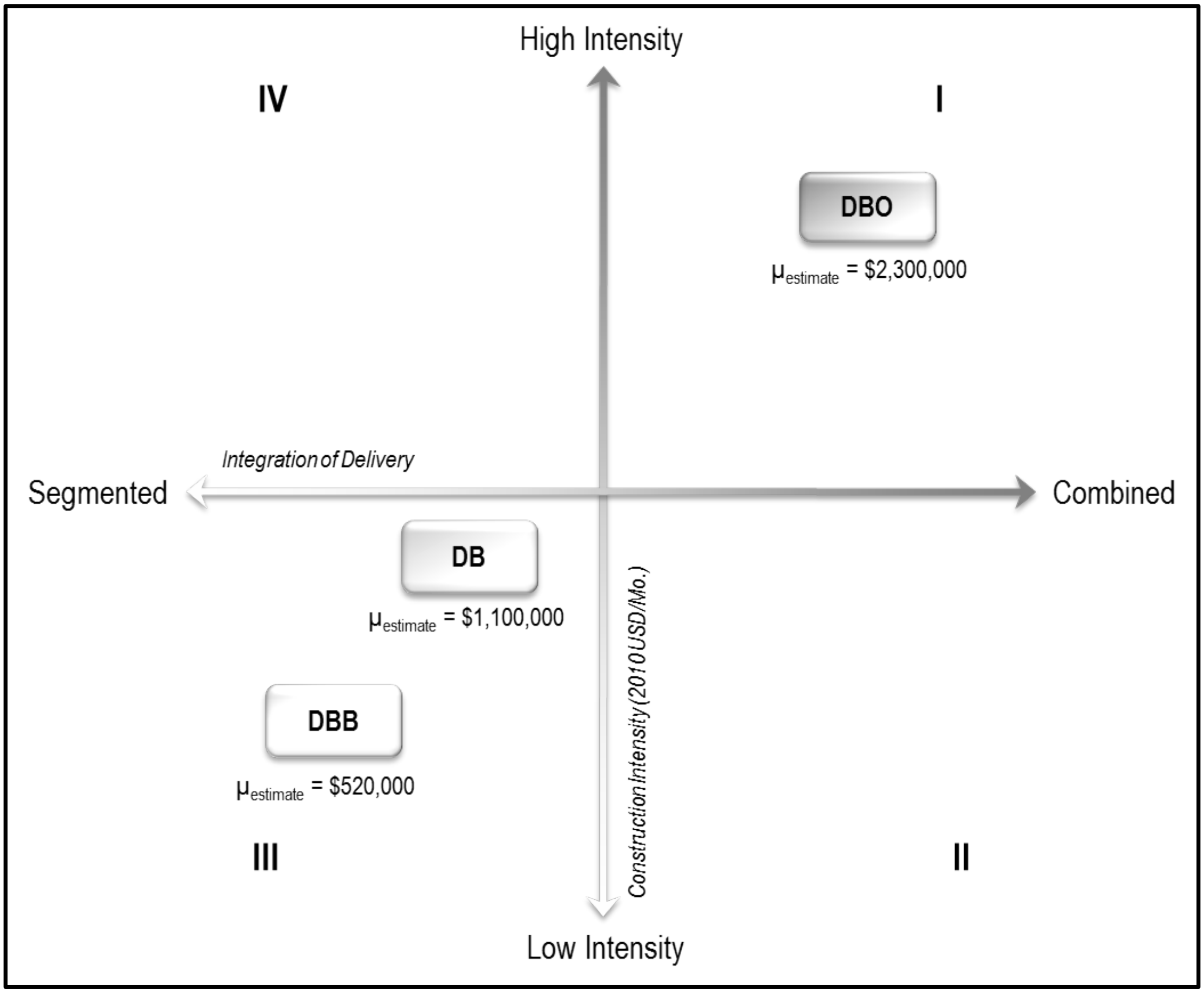

Figure 5.1: Analysis Results

Discussion of Results

The results from all three analyses indicate that it is statistically valid to infer that a more integrated PDM shows a direct correlation to a higher degree of CI for water/wastewater projects. However, there may exist underlying factors and characteristics in each data sample set used in the analysis that contribute to this relationship beyond simply the delivery method's level of integration. This is evident in the observation that DB and DBO PDMs compress D&C schedule durations in a similar manner and thus should theoretically exhibit similar levels of CI if all other underlying factors and characteristics are consistent. However, this was not the finding of the analysis. In fact, DB data was shown to have shorter schedule durations, on average, than DBO data, yet DBO data exhibits a statistically greater degree of CI. This simple finding confirms the speculation that characteristics inherent in the collected samples, other than the level of integration and CI, may be contributing to the results.

The different factors that may be impacting the results are: 1) the scale of DBO and DB projects compared to DBB projects and the types of technologies employed; 2) the size of the contractors designing and building DBO and DB projects; 3) schedule interruptions in a project's D&C duration; and 4) the status of the projects in the collected data. The true number of underlying characteristics that may be impacting the results is likely more than what is discussed here. However, these factors were determined to be those that would likely have the *greatest* impacts.

The CI metric is highly dependent and directly proportional to D&C hard costs. Therefore, projects with a larger capital cost have the potential to increase CI, even when these projects are not delivered using a more integrated PDM. Water/wastewater projects frequently involve the implementation of new technologies and systems, which can be expensive and significantly increase D&C costs. The Bogus et. al. (2008) research study identified 17 different water/wastewater technologies that exist and the differences in these technologies may significantly affect the D&C cost for each project data point. For instance, if a highly technical and expensive project element is installed in a short time frame in comparison to a non-expensive element installed over a larger time frame, the CI values for that time period will be significantly different. Overall, DBO projects represented in this research exhibit larger D&C capital costs than their DB and DBB counterparts, and this may be contributing to the findings of this research.

In addition to the capital size of a project, the size of the contractor delivering a project is a factor that may be associated with the results as well. Larger projects typically require the capacity and expertise of larger contractors. In general, larger contractors have the capability and resources to deliver projects with a greater degree of haste and efficiency than smaller contractors. Therefore, if DBO projects exhibit larger capital costs across the board, it is likely these projects are being delivered by larger and more experienced contracting firms. This may have a significant impact on the ability to compress a project schedule and is likely magnified by the DBO PDM's ability to overlap the D&C project phases. Overall, this can be contributing to the significant differences between DBO, DBB, and DB CI values.

The third factor that may be contributing to the results is schedule interruptions during the D&C phase for all projects. There exists the probability that there may have been starts and stops during D&C across all sample sets. Interruptions may have occurred as a result of funding or budgeting issues, design and construction errors or significant changes, problems with obtaining permitting, licensing, and bonds, or simply at the owner's request. Though the literature review reveals integrated PDMs normally exhibit an advantage in terms of delivering projects within a specified schedule, all projects are subject to schedule risks, which would impact the CI findings. However, it is more likely that DBB projects would be exposed to a *greater* degree of schedule risk than DB and DBO projects. Therefore, projects exhibiting large stoppage intervals may be skewing the DBB data, making the difference between the DBB and DB/DBO sample sets more dramatic.

Finally, the status of every project may have a significant impact on the values of CI as the status may have an influence on both the D&C costs and duration. Because DBO projects have not been as commonly executed as DBB and DB projects in the past, a handful of DBO data stems from projects still under construction or in the programming phase. The D&C costs and duration for these projects are only estimates provided by the project participant, and the true costs and durations for these projects may vary from what is collected and used in the analysis. Additionally, there are some DBB data points that are also still under construction, and therefore still subject to cost or schedule changes. Overall, these estimates, along with the other factors discussed, will have an impact on the true CI values for each data point.

This discussion has presented four factors that may be significantly influencing the results of this research. These factors are: 1) the scale of DBO and DB projects compared to DBB projects; 2) the size of the contractors designing and building DBO and DB projects; 3) schedule interruptions in a project's D&C duration; and 4) the status of the projects in the collected data. Because there is little information collected on these influencing factors, it is difficult to speculate to what degree these may or may not be skewing the results.

Potential Application of Findings

Quantifying CI for a range of PDMs exhibiting both segmented and integrated characteristics may have worthwhile applications for the construction industry. Specifically, this research looks to apply these findings to the selection of PDMs by owners in delivering public infrastructure water/wastewater projects. To do so, a literature survey of the current state-of-practice for delivery method selection as well as the associated consequences will be presented. This is followed by an alternative solution found in the literature survey and current methods for PDM selection. These methods are then aggregated into best strategies for PDM selection in the water/wastewater sector based on the common goals of these types of infrastructure projects. The ideas are merged together along with a need for research in this area to develop a subsequent point of departure for this research application.

To determine if this alternative solution is applicable, five of the DBO water/wastewater projects used as data in this research are further examined to determine what, if any, benefits exist from utilizing an integrated PDM to deliver the project and services as opposed to a more segmented PDM. They are also investigated to determine if there are any project attributes that can be accredited to an increased measure of CI.

Current State-of-Practice for Delivery Method Selection

Federal, state, and local governments began exclusively relying on the traditional DBB delivery method in the 1950s (Miller et. al, 2000; Miller 1997; Pietroforte and Miller 2002; and Westerhoff et. al, 2003). Additionally, the Environmental Protection Agency (EPA) Construction Grants Program and the Interstate Highway System Program saturated the delivery of public infrastructure projects with this method. Roughly two decades after WWII, the Brooks Act was passed which *required* the segmentation of design from construction on all public projects (Miller et. al. 2000). The act was passed with the belief that the segmentation of these practices would promote the most competitive and transparent delivery process. However, these restrictions often result in the minimization of an owner's ability to adequately define a project and explore the availability of alternative financing which has become a major issue for water and wastewater utilities (Miller et. al., 2000; and Westerhoff et. al., 2003). To a large extent, these restrictions and regulations have created a paradigm that constrains the availability of alternative delivery and financing methods and results in projects that are planned and designed to meet a budget rather than user needs and specific levels of service (Miller et. al., 2000; and Garvin et. al., 2000).

It is recognized that this current state-of-practice for delivering public infrastructure projects in the US is often ineffective, economically unsustainable, and falls short of achieving the best value for money (Miller et. al., 2000; and Pietroforte and Miller, 2002). Specifically, DBB delivery is economically unsustainable when considering the widening gap between the availability of public funds and the rapidly deteriorating state of the existing infrastructure system. The DBB PDM has continually created a fierce competition between public agencies over insufficient funds, facilitating a culture of planning for initial costs in lieu of a long-term sustainable approach considering life cycle costs (Pietroforte and Miller, 2002). The growing demand for new public infrastructure as well as repairing, rehabbing, or expanding outdated and unsafe systems to meet the demands of growing populations and expectations for higher levels of service further complicates the issue (CBO, 2002). The public is *demanding* that agencies and owners, specifically those providing water and wastewater services, become more cost-conscious about the way they spend each dollar (Westerhoff et. al., 2003). Owners and public sponsors are perpetually failing to realize that PDMs are variables that significantly affect the schedule, cost, and quality of public projects and may facilitate ways to be more efficient in spending public money (Miller, 1997).

The Consequences of the Current State-of-Practice for Water/Wastewater Utilities

Many governments across the world lack the financial resources necessary for building new and maintaining existing public infrastructure which, plays a crucial role in stimulating the global economies (Wibowo and Kochndoerfer, 2010). This circular relationship seems to be perpetually worsening, especially in the US. Holistically, the investments and funding available to expand, renew, and replace the deteriorating infrastructure of the US, in *all* sectors, is much less than is required (Garvin et. al, 2000). For example, the EPA conducted an investment "Gap Analysis" for clean and drinking water infrastructure needs in 2002. The analysis included a 20-year period from the year 2000 to 2019 and assessed the current levels of spending related to water infrastructure. The EPA concluded that a significant funding gap exists *and will continue to worsen* if the US maintains its current state of practice for delivering this type of infrastructure (United, 2002). The capital needs for clean water over this 20-year period were estimated to range anywhere from $331 billion to $450 billion and the estimated range for drinking water infrastructure anywhere from $154 billion to $446 billion (United, 2002). The analysis also compared the O&M needs for water infrastructure to the current spending habits of public funds on this phase of the production cycle. The EPA concluded that a significant funding gap for O&M of water facilities also exists and the gap is estimated to range anywhere from $72 billion to $229 billion (United, 2002). These capital spending estimates were compiled using historical data from the Congressional Budget Office and the U.S. Census Bureau.

Over the past 20 years, over one trillion dollars were spent on drinking water treatment and supply as well as wastewater treatment, disposal facilities, and infrastructure improvements (United, 2002). However, this has not kept up with the aging of the current system and the increases and fluctuations in populations stimulating a higher demand for these services. Not only this, but the EPA states current treatment methods may not even be sufficient, and the funding gap is contributing to a lack of investment in research and development to promote the use of more effective, efficient, and affordable treatment technologies. This can have dire health consequences for end users. For example, in 1993, the contamination of the Milwaukee water supply by cryptosporidium caused nearly 400,000 cases of illness and up to 100 known deaths (CBO, 2002). Moreover, the EPA estimates that overflows from sanitary sewers alone may be responsible for nearly one million illnesses each year (CBO, 2002). These outdated systems are currently responsible for discharging raw sewage into US surface waters at a rate as high as ten billion gallons each year and leaking out over seven billion gallons of clean water each day (ASCE, 2011).

The American Society of Civil Engineers (ASCE) compliments the EPA's gap analysis and provides similar estimates for funding needs. Overall, the ASCE scores the current state of water and wastewater infrastructure in the US with a "D minus" (D-) on its 2009 Infrastructure Report Card (ASCE, 2011). The physical condition of many of the nation's facilities remains poor as a result of a lack of investment in plants, equipment, and other capital improvements throughout the years. Not only this, but many systems have reached the end of their useful design lives. It is believed that this large deficit is correlated to the failure of infrastructure owners and sponsors to acquire and *sustain* support for the operations, maintenance, and rehabilitation of existing infrastructure (Miller and Barchan Foundation, 2010).

Overall, the water and wastewater infrastructure and distribution/transport systems in the US are deteriorating at a rapid rate and will be in need of replacements or upgrades in the very near future; however, it remains evident that there is insufficient public or federal money to resolve this issue. What is more interesting, is that increasing federal funding may not be the best solution to close this funding gap as there have been studies conducted by the CBO revealing that an increase in federal funding has previously led to the selection of more costly treatment technologies, the construction of a significantly over-built reserve capacity, and longer construction periods, all of which are detrimental to the goal of building and sustaining cost effective systems (CBO, 2002). Moreover, Miller (1997) states that with federal funding comes federal procurement rules which limit the options and alternatives available for owners, engineers, and managers. Therefore, it is ultimately individuals and households that will be burdened with the cost of investment necessary to build, upgrade, operate and maintain new systems directly through water and wastewater bills and indirectly through local, state, and federal taxes supporting these systems (CBO, 2002).

An Alternative Solution: One Size Does Not Fit All

Professionals in the engineering and construction community are beginning to realize the dramatic limitations of procuring the entirety of infrastructure projects with the same traditional PDM (Garvin, 2004). Coupled with these limitations are other combinations of: 1) a rapidly deteriorating infrastructure system; 2) a reluctance to raise taxes to fund infrastructure programs; 3) an increased presence of international and domestic investors willing to provide capital and services to the public; 4) the birth of infrastructure funds as a source of equity financing for projects; and 5) the recognition that private sector involvement can offer advantages in risk sharing, diversification, and steady cash flows for project (Garvin, 2010). This has resulted in more public owners at least *considering* the use of alternative delivery methods within the past ten to 15 years (Garvin, 2004). It is a critical decision, especially in the case of larger, more complex public infrastructure projects, to select the best project delivery system available (Ghavamifar and Touran, 2008; and Mafakheri et. al., 2007). Numerous authors believe that an "optimal project delivery system" exists for each and every individual project, and ultimate project success is dependent on the decision of selecting the most appropriate. Therefore, PDMs and finance methods alike should be considered variables in managing a public infrastructure project, not constants over which engineers, managers, and owners have no control or, at least, input (Miller, 1997; Mafakheri et. al., 2007; and Garvin et. al., 2000).

Integrated delivery methods offer project owners and developers an array of options for delivering public infrastructure projects effectively and efficiently. Recently, a significant shift in owner mentality from being primarily concerned with initial project costs, to considering other important factors such as design and construction quality, level of innovation, and level of service, has occurred (Miller et. al., 2000). Public project and program portfolios would best benefit end users if they are comprised of projects utilizing a wide array of delivery methods, including DBB, selected on the premise of what will provide the best value for money and highest levels of service rather than simply the lowest initial capital costs (Miller et. al., 2000; Miller 1997; and Garvin, 2004). Figure 5.1 presents a graphic description of what this new and "open life cycle" delivery strategy might look like for public agencies and owners.

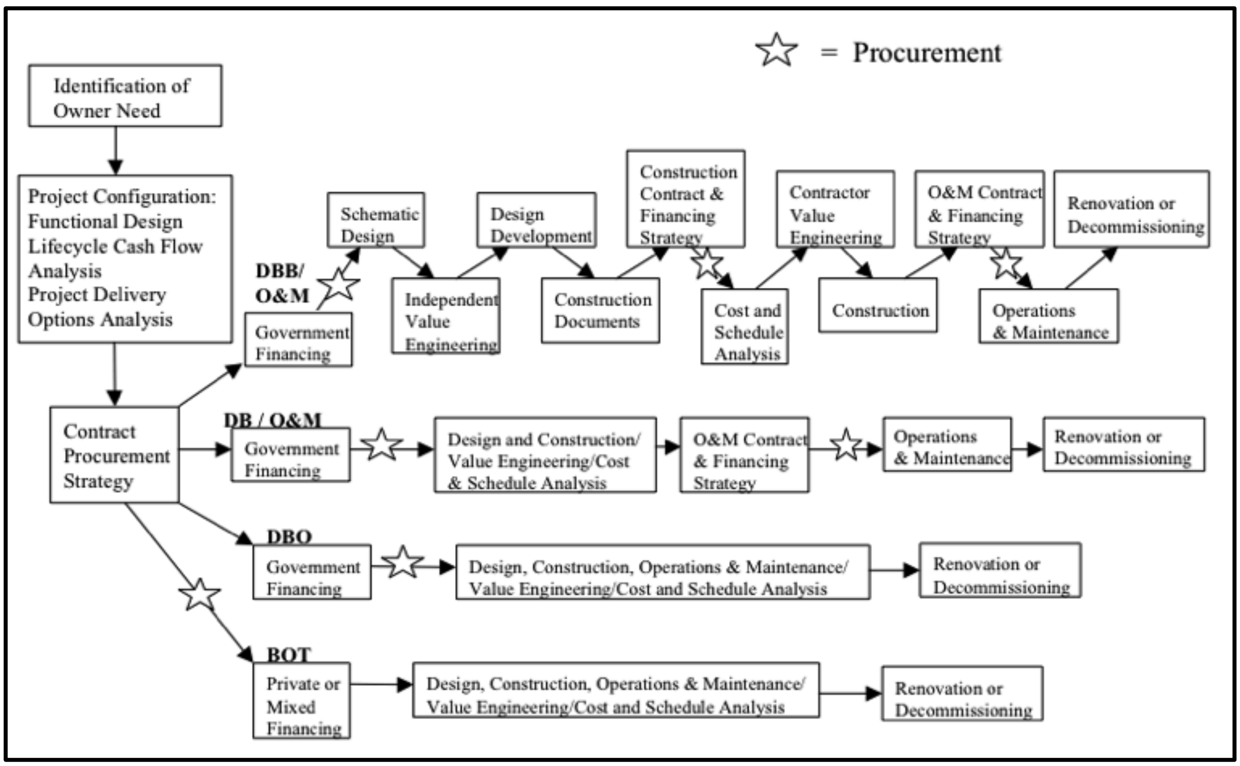

Figure 5.2: Open Life Cycle Delivery Portfolio for Public Owners (Miller et. al., 2000)

Gordon (1994) compliments this claim by stating the selection of the most appropriate delivery and contracting methods should begin with owners eliminating the obviously "inappropriate" methods, until the selection is narrowed and decision-makers can make an educated judgment as to which PDM will induce the most significant positive project outcomes in delivering project objectives. Simply following this process of elimination has been shown to reduce project costs by an average of 5%. When looking at multimillion-dollar projects, this savings is extremely significant (Gordon, 1994).

A shift towards the use of multiple delivery methods in public infrastructure project portfolios is suggested to improve the current state of national infrastructure assets through increased innovation and financing availability (Miller et. al. 2000). Using multiple methods allows for both the public and private sector to contribute in ways that complement one another while capitalizing on the inherent and natural strengths of each (Garvin, 2004). For example, the public sector excels at identifying public needs and the projects necessary to meet those needs, aligning economic and infrastructure strategies, providing a fair and competitive environment for private sector participation, establishing reliable commitments for financing, and imposing and managing external project factors such as permitting and environmental protection. Conversely, the private sector is best at developing, contributing, and introducing innovations in technology, design, construction, and operation processes, providing independent competitive checks of the technical and economic viability of projects, and providing an alternative source of capital in some instances (Miller et. al. 2000; and Garvin, 2004).

Specifically, in the case of water and wastewater projects, public owners are responsible for providing the highest levels of service in terms of supplying safe drinking water and environmentally safe wastewater services (Bogus et. al., 2008; and Westerhoff et. al., 2003). It is recognized that a major challenge remains in providing high levels of services and maintaining and operating facilities and distribution systems in a manner that is responsible, cost effective, and environmentally friendly (Westerhoff et. al., 2003). The CBO (2002) states that the "key" to cost effective water/wastewater systems actually resides in improving the O&M of the systems. Although the industry as a whole has become more efficient over the years in terms of O&M, it is estimated that the majority of owners are capable of reducing their operating costs by an average of 18% by simply applying more O&M "best practices" (CBO, 2002). Owners are turning to a wider array of project delivery methods to meet these needs and challenges, especially since a number of integrative PDMs include the O&M phase in the delivery (Bogus et. al., 2008). Westerhoff et. al. (2003) are in agreement with this view and have stated that over the past 10 years, a number of water utilities are looking to "do more with less" and have begun to look at alternative delivery methods to DBB as a way to do so. The need rests in analyzing the benefits of each PDM, and how the characteristics of each may be more appropriate for some water/wastewater projects than others.

Strategies for Selecting a PDM Found in the Literature

Selecting an appropriate delivery method can be challenging as a result of the extreme and subtle differences between project delivery methods, the unique characteristics of each project, and the large number of internal and external factors affecting the selection (Touran et. al., 2011; and Mafakheri et. al., 2007). Four PDM decision making strategies found in the literature are presented and then aggregated into a summary of "best strategies" for selecting the most appropriate delivery method for a unique project, specifically a water/wastewater project.

Strategy 1: AHP Process

Mafakheri et. al. (2007) have created and applied an Analytical Hierarchy Process (AHP) for decision-makers to use when determining which of the most prevalently used PDMs are most appropriate for any given project. Benchmarks were created and survey data gathered on 13 project factors and drivers that should be reflected in the AHP process. These drivers included cost, schedule, complexity, quality, and risk to identify a few. Although applying a mathematical model and framework to uncertainties and qualitative judgments can be difficult and imprecise, the model is useful in coercing decision-makers to evaluate a range of different PDM alternatives rather than simply utilizing the most traditional.

Strategy 2: Owner selection

Miller et. al. (2000) believe that effective PDM selection begins with addressing a project from the owner's standpoint. First, an owner should identify the needs of the project's end users with a basis in policies and goals. These needs should then be packaged into reasonable and executable projects. Next, the projects must then be aligned with the available PDMs, *after considering the entire array of available methods,* and how each will accommodate the different goals and needs of the public through significantly diverse tradeoffs between time, cost, and quality. Next, the owner must evaluate and select project proposals based on clear and objective criteria to keep transparency and public trust in the system high. Finally, owners must then manage the selected project contract to maintain cost, time, and quality control.

Strategy 3: Selection Based On Project "Drivers"

Gordon (1994) compliments the Miller et. al. (2000) strategy and offers one that is similar based on a process of elimination and a list of project drivers that should be assessed prior to selecting the most appropriate method. In Gordon's (1994) opinion, there is no single best method for any one project, but there are methods that are simply inappropriate in some cases. This is this author argues that the selection process should begin by simply eliminating those delivery methods that will not add value to a project—doing so will require a level of sophistication from the owner. After the number of methods has been tapered down, the owner must then assess a number of "project", "owner", and "market" drivers as well as how much project risk the owner is willing to allocate or accept. Project drivers that must analyzed include time constraints, flexibility needs, preconstruction service's needs, level of design process interaction, and financial constraints. Owner drivers include the owner's level of construction processes understanding, current capabilities in terms of staff commitment to a project, risk tolerance, restrictions or laws against using certain delivery methods, and other external factors such as selecting a particular contractor for strategic or political reasons. Market drivers that need to be assessed include the availability of the appropriate contractors, the current state of the market in terms of being competitive, and the package size of the project (determining if a project is too large or too small to facilitate a fair level of competition). Finally, the owner must assess risk in terms of the project itself and the financing alternatives available. Each delivery method will control these project drivers and allocate risk differently, based on the unique and inherent natures of each. After following this assessment, owners must then use their experience and best judgment to select the most appropriate method.

Strategy 4: Selection Based on Project "Factors"

Touran et. al. (2011) believe the selection of a PDM should occur as early as possible in the design phase and should be based on factors. A number of authors have concluded that factors and drivers such as schedule compression, owner control, risk allocation, construction claims, and cost growth are the most frequently cited in literature and should be considered in the selection framework (Touran et. al., 2011). Specifically, recent research has found that the following factors and drivers for selecting a PDM occurred most frequently in interviews with agency personnel: 1) reduce/accelerate project schedule; 2) encourage innovation; 3) establish a project budget early to establish cost certainty; 4) receive early construction contractor involvement; and 5) accommodate flexibility needs during construction (Touran et. al., 2011). These interviews with agency personnel led these authors to develop a framework examining 24 different project factors in five different categories including project-level issues, agency-level issues, public policy/regulatory issues, life cycle issues, and other issues.

Aggregated Best Strategies for Water/Wastewater Projects

Overall, PDMs for delivering water/wastewater projects should be selected after clearly defining project-specific goals and objectives (Westerhoff et. al., 2003; and Miller et. al., 2000). Water and wastewater utilities typically embody four goals when delivering capital projects: 1) ensuring the quality of the designed and constructed project; 2) controlling life-cycle costs; 3) creating a project that will permit effective and efficient operation and maintenance; and 4) completing the project within the required schedule (Westerhoff et. al. 2003). Therefore, the PDM selected must be capable of preserving the integrity of these objectives. Furthermore, owners must *understand* and evaluate all possible alternative methods that are consistent with their individual risk tolerance thresholds and desires for control over the entire production cycle, as some alternatives relinquish this control to the producer (Gordon, 1994; Westerhoff et. al., 2003; and Touran et. al., 2011). The owner must also carefully assess both the short and long-term financial implications of specific PDMs and determine which is the most appropriate for the current needs and financial constraints (Westerhoff et. al., 2003; and Miller et. al., 2000). The need for innovative technology, desire for contractor input in the design phase, and demand for flexibility during construction should all be considered. Other elements that must be evaluated include the inherent structure of contractual relations for each PDM, laws and regulations governing the use of specific methods, effective risk allocation strategies, and procurement and payment methods needed to support the PDM (Ghavamifar and Touran, 2008).

Point of Departure for the Application of Findings

The literature survey uncovered and merged together four primary ideas to create a research application point of departure. The first is that it is critical, especially in the case of larger, more complex public infrastructure projects, to select the best project delivery system available. Owners should select the "most appropriate" PDM through the elimination of inappropriate methods based on project factors/drivers and judgment. Numerous authors believe that an "optimal project delivery system" actually exists for individual projects, and project success is dependent on the decision of selecting the most appropriate. Therefore, PDMs and finance methods alike should be considered variables in managing a public infrastructure project, not constants over which engineers, managers, and owners have no control or input. However, Touran et. al. (2011) states that few actual decision-making frameworks for selecting an appropriate project delivery method exist, and even fewer exist for publically funded infrastructure projects.

The second idea contributing to the point of departure is that the current state of practice for delivering US public infrastructure is not sustainable. The sole reliance on DBB delivery is proving to create dire consequences for owners and end users. Overuse of the traditional DBB PDM is forcing owners to align their project goals with the process itself, and consequently configuring projects and limiting project scope to the availability of public money, rather than designing projects to meet long-term public needs. Life cycle O&M processes are being left out of the design equation on a consistent basis. Specifically for the water/wastewater utility industry, professionals and consultants agree that advancements in O&M efficiency will need to increase to sustain a shortage of financial resources available to meet all the needs and demands placed on the existing infrastructure systems by the public. Now, and within the last two decades, more and more water utilities continue to “reevaluate” the use of the traditional DBB delivery system and consider the use of more alternative delivery methods as they look to “do more with less” (Westerhoff et. al., 2003).

Thirdly, different PDMs offer inherently different benefits and limitations when applied to a project. However, if an informed decision maker selects a PDM, the benefits can be maximized for a specific project. For the most part, owners are proficient at identifying their desired project outcomes and outputs. Subsequently, most are also well versed in identifying project goals and objectives that will achieve these desires. However, it is clear that the majority lack the decision-making tools and/or judgment to select a PDM that facilitates the accomplishment of these goals. Numerous authors have identified a wide range of limitations and benefits for the fundamental PDMs (DBB, DB, and Construction Manager @ Risk). The literature survey in this study aggregates the findings for both segmented and integrated delivery method benefits and limitations in Tables 2.3 and 2.4.

The fourth idea is that a measure known and defined as CI by Konchar and Sanvido (1998), a measure of design and construction costs per unit time, would be useful as a project-level factor for PDM selection by owners. This is because owners continually consider cost and schedule critical elements to a project’s overall success. Additionally, Westerhoff et. al. (2003) believe that, "Long-term experience with alternative delivery methods is limited in the US, so due diligence is essential in the decision making process and the eventual use of methods with which the utility lacks experience”. However, hard statistics related to the use of alternative delivery methods for water/wastewater utilities are not easily found, making it difficult to make PDM decisions based on empirical evidence or data. This includes statistics related to CI for DBO water/wastewater projects. Table 5.1 below represents how these ideas from various authors merge together to form the point of departure for this industry application.

Table 5.1: Application Point of Departure Table of Converging Ideas

Subsequent Point of Departure for an Application of the Research Findings	
Concept	**Sources**
Need for a Decision Making Process in PDM selection	Ghavamifar and Touran 2008; Gordon, 1994; Mafakheri et. al., 2007; Miller 1997; and Touran et. al., 2011.
Unsustainable State-of-Practice for PDM Selection	Miller, 1997; Miller et. al., 2000; Pietroforte and Miller, 2002; Garvin, 2004; and Garvin et. al., 2000
Benefits and Limitations of Integrated PDMs	Westerhoff et. al., 2003; Dahl et. al., 2005; Konchar and Sanvido, 1998; Ghavamifar and Touran, 2008; Bogus et. al., 2008; Pietroforte and Miller, 2002; Garvin, 2004; and City, 2010.
Construction Intensity	Konchar and Sanvido, 1998; Gransberg and Buitrago, 2002; Bogus et. al., 2008
Need for Hard Statistics and New Data in PDM Selection	Westerhoff et. al., 2003; Bogus et. al., 2008

To determine if this alternative solution is applicable, five of the DBO water/wastewater projects used as data in this study were further examined to determine what, if any, benefits exist from utilizing an integrated PDM to deliver the project and services as opposed to a more segmented PDM. They are also investigated to determine if there are any project attributes that can be accredited to an increased measure of CI value. Tables 5.2 through 5.6 present the information found for each of the projects. Table 5.7 is an aggregation of the results with a brief discussion as to why the findings are applicable to this study.

Table 5.2: Tolt Water Treatment Facility DBO Project

The Tolt Water Treatment Facility	
Project Details	The facility provides 120 MGD of water to customers in Seattle and nearby suburban cities. It is Seattle's first filtration and ozonation facility. The plant was built under a Public-Private Partnership between Seattle Utilities and Azurix CDM and is currently executing a portion of its 25-year operating term. It opened in 2000 and was Designed, Built, and Operated under a $101 Million DBO contract.
Location	Seattle, Washington USA
Status	In operation
Contract Type	Design-Build-Operate (DBO) with a 25-year operate/maintain term
Contract Cost	Initially estimated at $156 Million
D&C Duration	1998-2000
Benefits of Using an Integrated Delivery System	1. Economic analysis and market feedback concluded DBO to be the least cost approach over the long term 2. Estimated $70 Million in cost saving for rate payers buy using the DBO delivery instead of Traditional DBB 3. The DBO contract is performance-based allowing the project to be complete in the most efficient and practical manner 4. Facilitated cooperation and collaboration between site permitting specialists, designers, constructors, and operators allowing each to "push the design envelope and be innovative" 5. Contract explicit about water quality, supply, and maintenance 6. Single point of accountability fostering better quality, a faster schedule, and a lower cost 7. City was able to obtain the most reliable and efficient technology at the lowest life-cycle cost
Sources	1. Seattle Public Utilities (2011) 2. American Water (2011)

Table 5.3: Cedar Water Treatment Facility DBO Project

Cedar Water Treatment Facility	
Project Details	The Cedar Water Treatment Facility was Designed, Built, and Operated under a 25-year DBO contract for which CH2M Hill is the producing party and Seattle Public Utilities is the owner. It is one of the first and largest facilities in the US to combine ozonation and UV treatment technology to treat drinking water. The facility treats 180 million gallons of water per day but is expandable up to 275 MGD. The operations building for the facility was designed and constructed to achieve LEED Gold certification.
Location	Seattle, Washington USA
Status	In Operations Phase
Contract Type	Design-Build-Operate (DBO), 15-year operations term with the opportunity to secure 10 additional years of operation at the cities discretion
Benefits of Using an Integrated Delivery System	1. Higher quality drinking water treated with state-of-the-art ozonation and ultraviolet treatment (improved taste and less odor) 2. Operations with less staff as a result of the innovative DBO process 3. Estimated $50 million in savings utilizing the DBO delivery method over the conventional DBB with the city operating the facility system. 4. Project schedule was shortened "significantly" 5. Designed to minimize impacts to the environment including: avoiding impacts to wetlands by using a dispersed site layout, minimizing building footprints, reusing existing infrastructure, and upgrading wetland habitat through native plantings. 6. Approximately 85% of the waste generated during construction was recycled 7. Because the state and federal regulation agencies are less familiar with the DBO process, the plant was required to meet and comply with more current and anticipated regulations ensuring "unquestionably" healthy drinking water would be provided 8. The producing party was able to integrate design and construction to achieve team-defined outcomes in minimizing environmental impacts and increasing water quality and constructability
Source	1. The National Council for Public-Private Partnerships (2011)

Table 5.4: East Providence Rhode Island Wastewater System DBO Project

East Providence Rhode Island Wastewater System	
Project Details	The city of East Providence has identified a facility plan to improve the existing wastewater treatment plant through the implementation of a biological nitrogen removal system, upgrades to the electrical, instrumentation, and odor control systems, and a new Watchemoket Pump Station and related force mains and sewers.
Location	East Providence Rhode Island
Status	Project Awarded to United Water
Contract Type	Design-Build-Operate (DBO), 10-year operations term with the opportunity to secure 10 additional years of operation at the cities discretion
Capital Cost	$52.5 Million
Duration	2010-2013
Benefits of Using an Integrated Delivery System	1. Competition on Design and Operate phases, not just Construction 2. One company provides for aggregation of services under one full service contract 3. Cost savings estimated to be $13.3 million over the traditional Design-Bid-Build approach 4. Optimized balance between capital and operating costs 5. Full innovation risk transfer 6. Single source of accountability 7. Fixed and predictable short and long term costs—rate stabilization 8. City maintains ownership and sets rates 9. Existing employees operating facility will be offered employment at a comparable compensation
Source	1. City of East Providence (2010) 2. Environmental Protection (2011)

Table 5.5: Tampa Bay Surface Water Treatment Plant DBO Project

Tampa Bay Surface Water Treatment Plant	
Project Details	The Tampa Bay Surface Water Treatment Plant was constructed to meet a population growth in the 1990s that was outpacing the needed drinking water supply and development of new ones. The facility provides 66 million gallons of water per day. It was built around the following objectives: 1) to create a new, environmentally friendly surface water treatment plant that would provide high-quality drinking water at the lowest cost possible, and 2) the system must be able to handle a wide range of flow rates and water quality standards set by local, state, and federal agencies. It is one of the largest DBO contracts in the US and incorporates automation and some of the most advanced industry technologies including: high-rate ballasted flocculation, ozone disinfection, and biologically active granular activated carbon filtration.
Location	Tampa Bay, Florida
Status	In Operation as of 2002
Contract Type	Design-Build-Operate (DBO), 15-year operations term with the opportunity to secure 5 additional years of operation at the city's discretion
Contract Cost	$144 Million
Duration	28 Months
Benefits of Using an Integrated Delivery System	1. Estimated $85 Million in savings over the contract lifecycle 2. Savings passed on to ratepayers 3. A six-week pilot-testing program concluded that the advanced technologies produced higher water quality, improved process reliability, lower treatment costs, and a 20% reduction in space requirements. 4. Facility meets water quality standards that are three times greater than those required by the US EPA's Safe Drinking Water Act and State regulations 5. Savings in operations and labor costs as the facility is highly automated and user friendly. The plant is able to operate with a staff of only 16 6. Fast track delivery and a "seamless flow" between major project elements and phases—Jack Rebholz, P.E., PMP, and senior project manager
Sources	1. The National Council for Public Private Partnerships (2011) 2. Rice, Amanda, and Thomas, Nicole (2009)

Table 5.6: Twin Oaks Valley Water Treatment Plant DBO Project

Twin Oaks Valley Water Treatment Plant	
Project Details	The Twin Oaks Valley facility is the world's largest submerged membrane filtration water treatment plant. The project involved the design, construction, and operations of a 100MGD plant and related flow control facilities as well as a 15MG clear well storage tank. The membrane treatment process produces higher quality water at a less expensive rate than other, more conventional, processes. It is also more environmentally friendly.
Location	San Diego, California USA
Status	In Operation as of 2008
Contract Type	Design-Build-Operate (DBO), 20-year operations term
Contract Cost	$262 Million (Total Lifecycle Estimate)
Duration	2005-2008
Benefits of Using an Integrated Delivery System	1. Energy and money savings. Designed to utilize gravity to transport treated water to the aqueduct system rather than energy-intensive pumping processes 2. High quality of water as a result of the highly technologically advanced submerged membrane process 3. Environmentally friendly as the plant uses fewer chemicals than conventional plants. It produces minimal byproducts 4. High efficiency—designed so that almost every drop entering the plant leaves as high quality drinking water 5. Emphasis on safety resulted in over 612,000 work hours without a lost time accident
Sources	1. San Diego County Water Authority (2011) 2. CH2M Hill (2011)

Table 5.7: Summary of DBO Project Findings

DBO Water/Wastewater Projects					
Description	**Tolt WTF***	**Cedar WTF***	**E. Providence RI WTF***	**Tampa Bay SWTP***	**Twin Oaks Valley WTP***
Large Scale Project	✓	✓		✓	✓
Innovative Technology	✓	✓	✓	✓	✓
Compressed Schedule		✓		✓	
Consideration of O&M in Design		✓	✓	✓	✓

*WTF = Water Treatment Facility
*SWTP = Surface Water Treatment Plant
*WTP = Water Treatment Plant

From the additional project data collected in Table 5.7, 80% of the DBO projects are considered large-scale projects either because they exhibit a high capacity, in Million Gallons per Day (MGD), and/or high capital costs. All of the projects were said to have utilized new or innovative technologies leading to increased O&M efficiencies. Additionally, 40% of these projects specifically mentioned the reduction of the project's duration as a result of utilizing the

DBO PDM. Finally, 80% of the projects implied that O&M processes were considered early on and designed for, resulting in lower costs to the owner as well as higher levels of service to the end users. These findings correlate to what was found in the literature regarding integrated PDM benefits as well as to the finding of this study that a more integrated PDM is capable of producing projects at a higher level of CI when compared to more segmented PDMs.

Overall, the quantified data and application provides evidence that more intense projects *would benefit more* from the use of integrated PDMs. This is inferred from the data analysis, literature survey of the current state-of-practice for project delivery, and the summary of integrated and segmented PDM advantages previously discussed. To help support this statement, a scenario where a utility owner may use these findings to help in the selection of a PDM is presented.

Scenario for Utilizing Construction Intensity in PDM Selection

A scenario in which owners may benefit from the collection of CI data across various PDMs is in instances where there exists a predetermined budget and schedule for a project and the traditional DBB PDM cannot meet the requirements of this constraint due to its inherent limitations. Though it is clear that there are various factors that should be considered in the selection of a PDM, the ability of a PDM to meet budget and schedule requirements is often considered *critical* to owners. Therefore, the ability of a PDM to deliver a project within a specified level of CI may help sway an owner in the direction of selecting a more integrated PDM for that specific application where otherwise, the selection of an integrated PDM would have been overlooked. Overall, it is the hope of this research that statistics regarding CI for various PDMs can be effectively used by owners to help decision-makers make better procurement decisions.

Research Contribution

The overall goal for this research investigation was to provide owners and industry professionals with a quantitative measure to add to existing methodologies for selecting delivery methods as well as contribute to the current literature related to PDM selection. The potential broader impacts of this study would be to persuade more public owners to consider comprising project portfolios of various delivery methods, rather than strictly DBB. In doing so, it is believed by John B. Miller and other recognized authors that the state of the current infrastructure in the US and funding gap that exists may be closed quicker than if owners solely rely on the current state-of-practice. The measureable changes that could be produced from this study would be at the industry level—There would be an increase in the number of public projects using alternative delivery methods or at least the number of owners willing to consider the use of alternative delivery.

Further Research

The possible extensions of this study would be to include more PDMs in the data set such as: 1) Turnkey delivery; 2) pure Operations and Maintenance contracts; 3) Design-Build-Finance-Operate-Maintain; and 4) Build-Operate-Transfer to name a few. As delivery methods and hybrids of delivery methods evolve, this list should expand. Additionally, including elements such as: 1) the scale of the projects and types of technologies employed; 2) the size of the contractors designing and building the projects; and 3) schedule interruptions in a project's D&C duration in the analysis of the results would be beneficial for future research to determine the adequacy of utilizing a comparison based on CI values across PDMs.

DEFINITIONS

Construction Intensity:

Construction intensity will be defined as the dynamic project performance measure of project design and construction costs, in US dollars, divided by design and construction duration, in months.

Design and Construction Hard Costs:

Hard Costs will be defined as only the capital costs related to design and construction. No other soft/indirect costs, costs for permitting, or other owner related fees were considered Hard Costs.

Integration Continuum:

The integration continuum is defined by the Miller et. al. (2000) framework and divides segmented PDMs from more integrated PDMs. The degree of this division depends on the degree of collaboration and communication between key party players: the owner, designer, builder, and operator.

Production Cycle:

A project Production Cycle will be defined as encompassing all phases common to any project including, programming/planning, design, construction, and operations and maintenance.

Project Delivery Method (PDM):

A project delivery method will be defined as "a system for organizing and financing design, construction, operations and maintenance activities that facilitates the delivery of a good or service" (Miller et. al., 2000).

Public Infrastructure:

Public infrastructure will be defined as products or services delivered to the public and under the control of public owners.

ABBREVIATIONS AND SYMBOLS

A/E: Architect/Engineer
ADM: Absolute Deviation from the Median
AHP: Analytical Hierarchy Process
AMSA: Association of Metropolitan Sewerage Agencies
ANOVA: Analysis of Variance
ASCE: American Society of Civil Engineers
AWWA: American Water Works Association
CBO: Congressional Budget Office
CCI: Construction Cost Indices
CIFE: Center for Integrated Facility Engineering
CM/GC: Construction Manager, General Contractor
D&C: Design and Construction
DB: Design-Build
DBB: Design-Bid-Build
DBO: Design-Build-Operate
df: Degrees of Freedom
ENR: Engineering News Record
EPA: Environmental Protection Agency
ISDR: Infrastructure Systems Development Research
MGD: Million Gallon Per Day
n: Sample Size
NT: Natural Tolerance
O&M: Operations and Maintenance, Operate and Maintain
P3: Public-Private Partnership
PDM: Project Delivery Method
QBS: Qualifications Based Selection
RFP: Request for Proposals
RFQ: Request for Qualifications
RSD: Random Sampling Distribution
SRF: State Revolving Fund Loan
US: United States
WWII: The Second World War
$\gamma 3$: Skewness
$\gamma 4$: Kurtosis
σ^2: Variance
μ: Mean

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APPENDIX A

PUBLIC INFRASTRUCTURE FINANCING AND DELIVERY QUESTIONNAIRE

The objectives of this questionnaire are to support a Master's Thesis seeking to determine if there is a correlation between construction intensity (CI = MGD*Cost/Duration) and the project delivery method used for water/wastewater projects in the United States.

Project Information Provided:
The intent of gathering this high-level project information is to analyze the current trends of owners and contractors in delivering public infrastructure projects. There is **no intention** to specifically mention project names, project managers, owners, or contractors in any thesis, articles, or papers. However, in the rare instance providing a project name/information may be necessary, a follow up with the provider of the information will occur and **permission obtained beforehand**. **No project name or information will be specifically called out in any printed work unless confirmation has been granted to do so.**

Instructions for Filling out the Questionnaire:
Right clicking a selection box and then left clicking "properties" will allow you to "check the box" after the properties dialog box opens. Simply clicking within a gray shaded box to provide an explanation will allow you to type a response. Please send the document back when complete. If there are any issues opening or sending back the questionnaire, please contact:

Desiderio Navarro
University of Colorado at Boulder
Construction Engineering and Management
Civil Engineering Master's Candidate and Research Assistant
Desiderio.Navarro@colorado.edu
303.902.4047

Participant Information

Participant Name:
Relation to the Project:
Email Address:
Or Phone Number:

I. Background Information

1. Project Name and Brief Project Description:

Project Name:

Project Capacity (million gallons per day or million gallons storage):

Brief Scope of Work Description:

2. **Status:**
   - ☐Planning/Programming
   - ☐Design/Construction
   - ☐Operational

   IF in operation, please specify the year operations began

3. **Type of Project:**
   - ☐New facility
   - ☐Repositioning of an existing facility (Routine Maintenance)
   - ☐Substantial alteration of an existing facility

4. **Location:**

   Street Address:

   City:

   State/Province:

5. **Delivery Method Used (Or Proposed) b/w *Owner* and *Primary Contractor*:**
   - ☐Traditional Design-Bid-Build (D/B/B)
   - ☐Construction Manager at Risk (CM @ Risk)
   - ☐Design-Build (DB)
   - ☐Design-Build-Operate (DBO)
   - ☐Other (Please Specify in gray box):

   IF DBO, please specify the length operations term in years and/or months

II. Project Procurement

6. **How were the major contracting parties procured?**
   - ☐Design and Const. Contracted Separately. Owner will Operate and Maintain Facility
   - ☐Design and Const. Contracted Separately. Owner will Contract Another Party to Operate and Maintain the Facility
   - ☐Design and Const. Contracted w/ Single Entity. Owner will Operate and Maintain Facility
   - ☐Design and Const. Contracted w/ Single Entity. Owner Contracts with Another Party to Operate and Maintain Facility
   - ☐Design, Const. Operations, and Maintenance Contracted with Single Entity for Specified Term. Facility will be turned over to owner after term is complete.
   - ☐Operations and Maintenance Contract for Long Term O&M of Facility Including Non-Capital Repairs

7. **Procurement Approach for Design and Construction based on the following:**

   QBS – Was the designer selected solely on the basis of qualifications, with price negotiated later?

   RFQ – Did the competition include an RFQ in which qualification of each Designer/Contractor was confirmed and/or the number of competitors narrowed?

   RFP – Was the Designer/Contractor chosen based on its response to an RFP in which price and other factors were evaluated?

   IFB – Was the Contractor selected using an Invitation for Bids in which price was the only evaluation criteria?

   Unsolicited Proposals – was the Designer/Contractor selected on the basis of an unsolicited proposal?

Design/Construction/Operations Procurement Method

☐QBS
☐RFQ
☐RFP
☐IFB
☐Unsolicited Proposal

8. Form of Contract Used:

☐AIA Document
☐AGC Document
☐FIDIC Document
☐EJCDC Document
☐Custom Document
☐Other

If Other, Please Specify:

III. Project Duration and Value

9. Initial/Proposed Design and Construction Duration:
(Years and Months)

10. Project Hard Costs:
Please provide Hard costs as opposed Hard+Soft Costs. This is to say initial project ***capital costs*** *minus all other owner related expenses such as permitting, fees, etc…*

Design and Construction:
Operations and Maintenance:
Total Project Cost:

Would you like a copy of my thesis work in the form of a brief article presenting the findings when complete?

☐Yes
☐No

If Yes, Please Provide and Email Address:

Thank You!

APPENDIX B

Data Analysis II: All Data Points

Introduction

This data analysis is performed on all the data collected for each PDM. Conducting an analysis on a full set of data caters to the view that every construction project is unique, and therefore, none should be eliminated when conducting an analysis to make inferences about an underlying research population.

Describing the Data Sets

The total number of data points for this analysis is as follows:

- DBB: 73 data points
- DB: 33 data points
- DBO: 38 data points

Table B.1 reveals the D&C duration data for each sample set.

Table B.1: Design and Construction Duration Data

Design and Construction Duration (Months)				
	DBB	DB	DBO	Units
Data Pts.	73	33	38	
Mean	38	21	26	Months
Median	36	18	26	Months
Mode	36	-	24	Months
Range	84	43	31	Months
Std. Dev.	18	11	7	Months
High	96	48	42	Months
Low	12	5	11	Months

From the table, DBB projects are shown to have, on average, a 206% longer D&C schedule durations than their DB and DBO project counterparts. There is not a single DBB project in the data sample that was completed in less than one year. Additionally, the largest D&C duration is found in a DBB project. DB projects showed the lowest average for duration values across all three data sets even though the range of duration data is similar for DB and DBO projects. This may be due to larger projects being constructed using the DBO PDM than DB PDM since both overlap design and construction phases and compress the project schedule in a similar manner.

Table B.2 presents the D&C hard cost data used in the study, and Figure B.1 is a graph representing the D&C capital cost data across all three PDMs.

Table B.2: Design and Construction Hard Cost Data

Design and Construction Hard Cost (2010 USD)			
	DBB	DB	DBO
Data Pts.	73	33	38
Average	$49,000,000	$39,000,000	$80,000,000
Median	$9,900,000	$15,000,000	$43,000,000
Mode	-	-	-
Range	$670,000,000	$150,000,000	$420,000,000
Std. Dev.	$110,000,000	$47,000,000	$85,000,000
High	$670,000,000	$160,000,000	$430,000,000
Low	$1,100,000	$3,000,000	$4,400,000

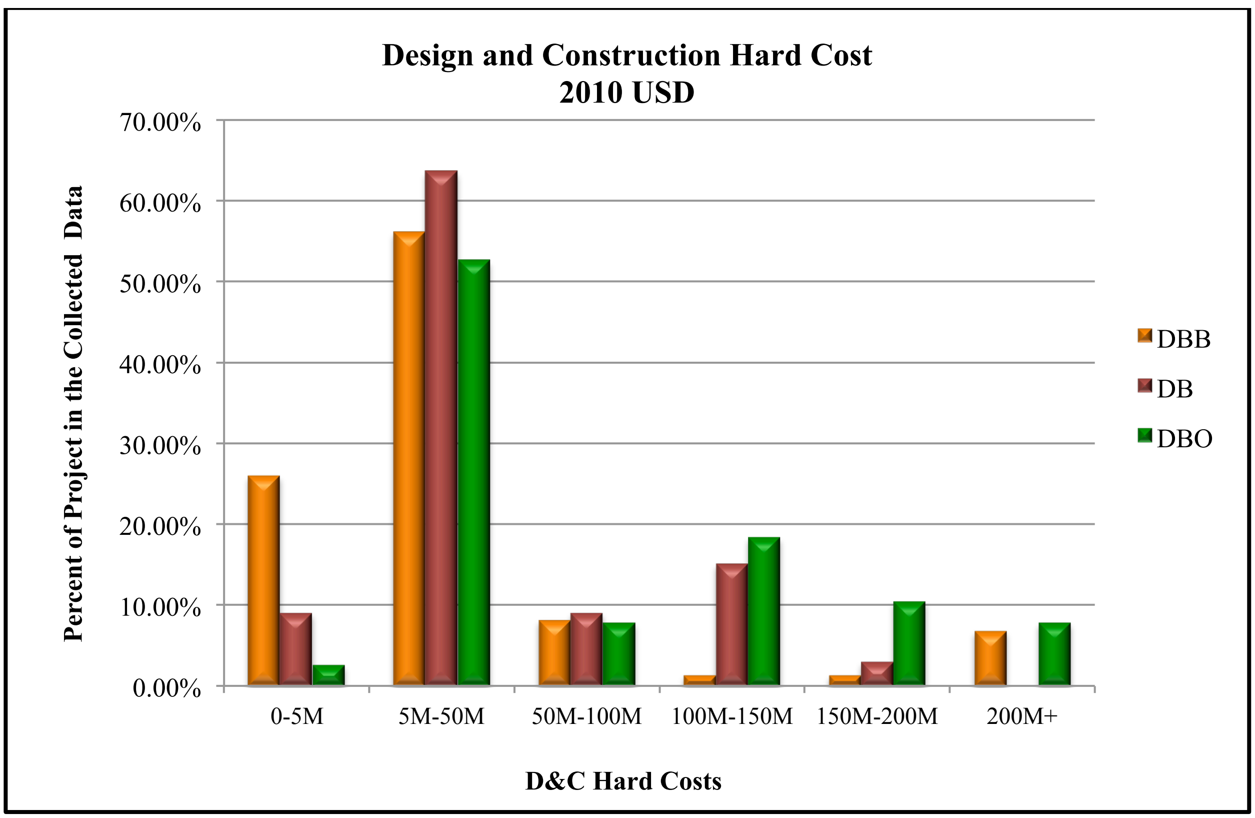

Figure B.1: Design and Construction Hard Cost Data

The hard costs across all three samples are comparable since all were brought to 2010 present values using Engineering News Records (ENR) Construction Cost Indices (CCI). To normalize the cost data, the annual CCI from ENR (2011) was used in the following manner:

$$D\&C\ Hard\ Costs\ (2010\ USD) = \frac{D\&C\ Hard\ Cost}{CCI\ (Design\ Year)} * CCI\ (Year\ 2010) \qquad \text{Eq. (B.1)}$$

All cost data was normalized from the year design began. The table reveals that, on average, the capital costs for the DBO data is nearly 163% higher than that for DBB projects. However, DBB projects, on average, exhibit higher hard costs for D&C than DB projects by nearly 125%.

Table B.3 presents the CI data for each PDM, and Figure B.2 is a scatter plot of CI values for each PDM sample set.

Table B.3: Construction Intensity Data

Design and Construction Intensity (2010 USD/Month)			
	DBB	**DB**	**DBO**
Data Pts.	73	33	38
Average	$970,000	$1,300,000	$2,700,000
Median	$400,000	$790,000	$1,400,000
Mode	-	-	-
Range	$9,900,000	$5,900,000	$13,000,000
Std. Dev.	$1,800,000	$1,200,000	$2,600,000
High	$9,900,000	$6,100,000	$13,000,000
Low	$17,000	$230,000	$210,000

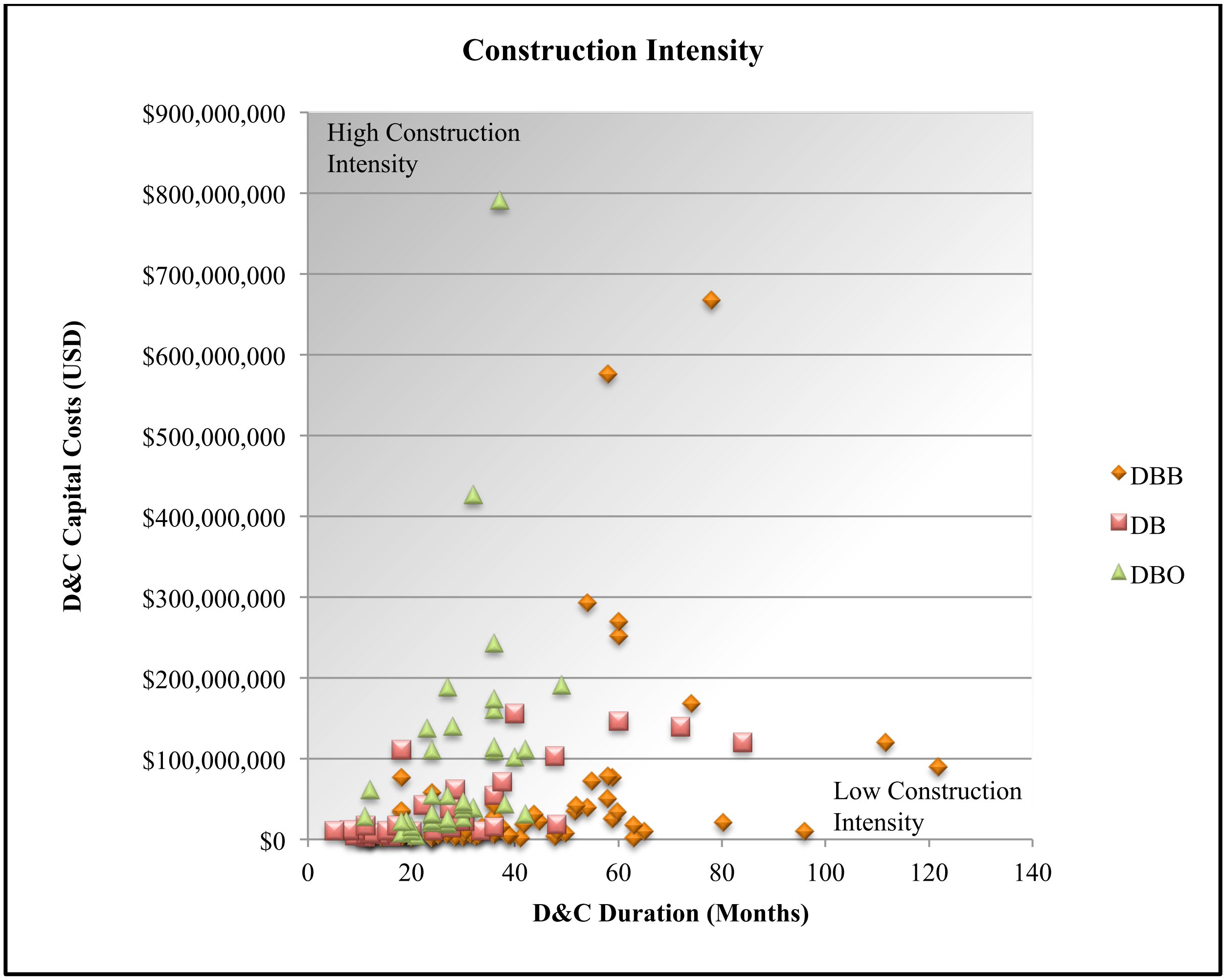

Figure B.2: Construction Intensity Data

Overall, DBO projects exhibit a greater degree of CI, on average, over its DB and DBB counterparts. This difference is nearly 278% greater when compared to DBB and 207% greater when compared to DB. Moreover, DB projects also exhibit a significantly greater degree of CI over DBB projects by nearly 134%. The medians of each data sample represent similar rankings as the averages. The DBO median for CI is 177% greater than the DB median and 350% greater than the DBB median.

Research Variables

The measurable variables for this investigation were both quantitative and qualitative. The quantitative parameters were: 1) D&C duration quantified by months; and 2) D&C hard costs normalized to 2010 USD. The degree of delivery integration represented the qualitative variable. Previous research by John B. Miller and the ISDR at MIT group coded PDMs using this degree as a parameter of classification. The findings from these research efforts were considered comprehensive, and therefore, were applied here.

The dependent research variable for this research was CI. The criterion measure for CI was D&C hard costs per D&C duration. The CI variable was considered underlying continuous, ratio data. Conversely, the independent research variable was the PDM level of integration classified by Miller et. al. (2000). This variable was measured quantitatively and was considered nominal data.

Table B.4 presents the descriptive statistics for the three data samples compared in the ANOVA.

Table B.4: Descriptive Statistics for the Data Samples

Descriptive Statistics						
PDM	**n**	**Mean**	**Std. Dev.**	**Low**	**High**	**Range**
(All)	144	1.6E+06	2.6E+06	1.7E+04	2.1E+07	2.1E+07
1	73	9.7E+05	1.8E+06	1.7E+04	9.9E+06	9.9E+06
2	33	1.3E+06	1.2E+06	2.3E+05	6.1E+06	5.9E+06
3	38	3.2E+06	4.0E+06	2.1E+05	2.1E+07	2.1E+07

Overview and Statistical Hypotheses

In order to answer the research question, the following statistical hypotheses were tested and answered in the following order:

Shape: Test for Normality (Moment Tests)

H_0: $\gamma3 = 0.00$ H_1: $\gamma3 \neq 0.00$

H_0: $\gamma4 = 0.00$ H_1: $\gamma4 \neq 0.00$

It is important to note that normality will be tested for the project data within each of the three PDM data sets individually, not in aggregate.

Spread: Test for the Dispersion of the Means

$$H_0: \sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$$

$$H_1: \sigma^2_{DBB} \neq \sigma^2_{DB} \neq \sigma^2_{DBO}$$

Location: Test for the Equality of Means

$$H_0: \mu_{DBB} = \mu_{DB} = \mu_{DBO}$$

$$H_1: \mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$$

Determining the Underlying Shape of the Research Population: Testing for Normality

When sample sizes contain less than 25 data points, the appropriate test for normality is the Anderson-Darling Test. In contrast, when sample sizes are greater than 25, the appropriate tests for normality are the moment tests in which skewness and kurtosis are tested separately. In this analysis, all sample sizes for each of the examined PDMs are greater than 25, and therefore, the moment tests were used. The following eight-step procedure was utilized for all three data sets simultaneously in testing for normality, as the results and procedure itself were similar for each.

Eight-Step Statistical Hypothesis Test Procedure for Normality

1. Underlying Assumptions of the Test For Normality:
    a. The data are continuous
    b. The data are from a sample that was randomly drawn from a process/population
       *Note: In this case, the data is not a truly random sample, but rather a sample by convenience.
2. The Test Hypotheses:

$$H_0: \gamma_3 = 0.00 \qquad H_1: \gamma_3 \neq 0.00$$

$$H_0: \gamma_4 = 0.00 \qquad H_1: \gamma_4 \neq 0.00$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:

   a. For The Moment Tests:

      i. Skewness—t-statistic

      ii. Kurtosis—standard table values for kurtosis

5. Random Sampling Distribution of the Test Statistic when H_0 is True:

   a. For moment tests

      i. Skewness—t-statistic (Approximate)

      ii. Kurtosis—simulated or normal (Approximate)

6. The Critical Value for Rejecting the Null Hypothesis:

$$\text{Reject } H_0 \text{ if p-value} < 0.05$$

7. Calculations:

   The calculations for normality were computed using the MVP stats software. The results of these computations are presented below in Table B.5. The yellow highlights denote p-values outside of the stated level of risk acceptance.

Table B.5: Testing for Normality

Normality Tests									
PDM	**N**	**Mean**	**Variance**	**Skewness**	**p-value**	**Kurtosis**	**p-value**	**W(E)**	**p-value**
(All)	144	1.6E+06	6.9E+12	4.0	0.000*	25	<0.02*	0.00	<0.007*
1	73	9.7E+05	3.1E+12	3.5	0.000*	13	<0.02*	0.00	0.0091*
2	33	1.3E+06	1.5E+12	2.0	0.000*	7.6	<0.02*	0.02	0.0178*
3	38	3.2E+06	1.6E+13	3.1	0.000*	12	<0.02*	0.02	0.0156*

8. Decide whether to accept or reject H_0:

   a. Decisions:

      i. Reject H_0 for DBB data set

ii. Reject H_0 for DB data set

iii. Reject H_0 for DBO data set

b. P-values

i. P-values for DBB data set: ≈ 0.000* and <0.02*

ii. P-value for DB data set: ≈ 0.000* and <0.02*

iii. P-value for DBO data set: ≈ 0.000* and <0.02*

c. There exists sufficient statistical evidence to infer that all three data sets are not normally distributed. Therefore, the underlying research population for each PDM can also be inferred to not follow a normal distribution.

d. Estimate of shape: Using the MVP stats histogram generation program, the distributions found to best fit all three data sets were as follows:

i. Two-Parameter Weibull distribution for DBB data with a fit of 0.953

ii. Two-Parameter Weibull distribution for DB data with a fit of 0.958

iii. Two-Parameter Weibull distribution for DBO data with a fit of 0.957

From the normality tests, it is clear that the data sets are *not* normally distributed and the number of data points in each set is not equal. Because of this, a traditional Fischer One Way ANOVA is not applicable. Therefore, Leven's Improved Test (Brown-Forsythe Test) for Dispersion, and a Welch test for central tendency were used.

Levene's Improved Test (Brown-Forsythe Test) for Dispersion

In order to conduct a Levene's improved test for dispersion on data that is not normally distributed and between sample sets of unequal size n, the ADMs for all three groups must first be computed. Doing so has been shown to significantly increase the effectiveness of the test (Luftig, 2011). These absolute values can then be compared using an ANOVA. The ADMs were found utilizing the MVP stats software. After calculating the ADMs, these data were transferred into SPSS to conduct the comparison analysis. The descriptive statistics for each PDM are presented in Table B.6.

Table B.6: Dispersion Descriptive Statistics for CI

Dispersion ADM Descriptive Statistics (CI)								
	N	Mean	Std. Dev.	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Minimum	Maximum
DBB	73	7.9E+05	1.7E+06	2.0E+05	4.0E+05	1.2E+06	0.0E+00	9.5E+06
DB	33	8.0E+05	1.0E+06	1.8E+05	4.4E+05	1.2E+06	0.0E+00	5.3E+06
DBO	38	2.2E+06	3.7E+06	6.0E+05	1.0E+06	3.4E+06	6.8E+04	2.0E+07
Total	144	1.2E+06	2.4E+06	2.0E+05	7.8E+05	1.6E+06	0.0E+00	2.0E+07

Eight-Step Test Procedure

1. Underlying Assumptions for Levene's Improved Test for Dispersion:
    a. The data are continuous
    b. The data was randomly drawn from a process/population

       *In this case, the data is not a truly random sample, but rather a sample by convenience.
    c. The underlying data is *not* normally distributed
    d. The data sets compared are of *unequal* size n
2. The Test Hypotheses:

$$H_0: \sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$$

$$H_1: \sigma^2_{DBB} \neq \sigma^2_{DB} \neq \sigma^2_{DBO}$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:
    a. F test statistic
5. Random Sampling Distribution of the Test Statistic when H_0 is True:

a. The F-statistic RSD (approximate value and calculated using MVP Stats, shown as Figure B.3) when $p = 0.05$, with $J - 1$ and $n_{total} - J\ df$ where:

i. $J = 3$, and

ii. n_{total} equals the total number of DBB, DB, and DBO data points

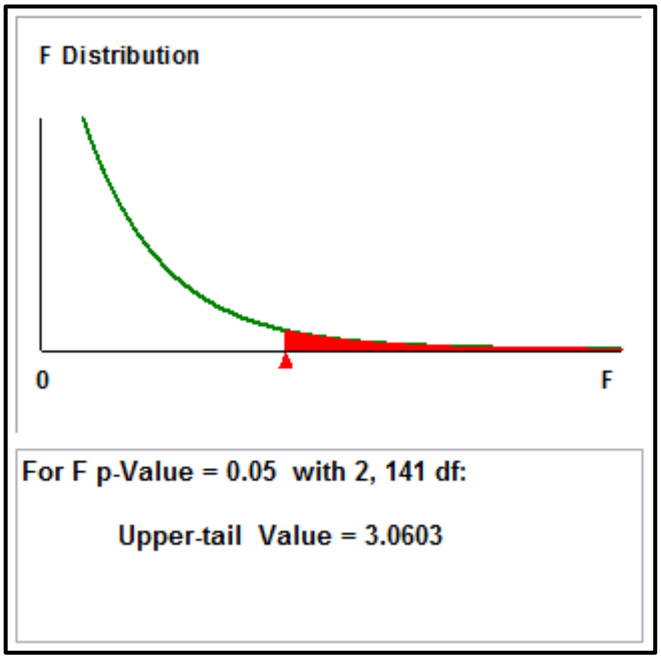

Figure B.3: F-Statistic Approximate RSD (Generated Using MVP Stats)

6. The Critical Value for Rejecting the Null Hypothesis:

Reject H_0 if $F > 3.0603$ and/or $P\text{-value} < 0.05$

7. Calculations:

The calculations for dispersion were done utilizing both MVP stats to generate the ADMs and SPSS to perform the ANOVA. The results of the Brown-Forsythe ANOVA test on the ADMs for the three PDM sample sets are presented in Table B.7.

Table B.7: Robust Test for Equality of Dispersion

Robust Tests of Equality of Means (CI ADMs)				
	Statistic*	df1	df2	Sig.
Welch	3	2	74	0.077
Brown-Forsythe	4.6	2	54	0.010
*Asymptotically F Distributed				

8. Decide whether to accept or reject H_0:

   a. Decisions—Reject H_0

   b. F and P-values for the Brown-Forsythe Test:

      iii. $F = 4.6^* > 3.0603$

      iv. $\text{P-value} = 0.01^* < 0.05$

   c. There exists sufficient statistical evidence to infer that:

$$\sigma^2_{DBB} \neq \sigma^2_{DB} \neq \sigma^2_{DBO}$$

Although the null hypothesis was rejected, this does not undoubtedly conclude that a significant difference occurs between *all* three PDM means. In fact, the null hypothesis can be rejected in instances where there exists a large difference between only two of the three data samples. To further determine the characteristics of this significant difference, a Post-Hoc analysis was warranted. The results of this analysis are presented below in Table B.8 to individually compare and assess the differences in the CI dispersion value means.

Table B.8: Post-Hoc Analysis of Variance (Generated Using SPSS)

Games-Howell Multiple Comparisons (CI)						
(I) PDM	(J) PDM	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
DBB	DB	-1.2E+04	2.6E+05	0.999	-6.4E+05	6.2E+05
	DBO	-1.4E+06	6.3E+05	0.072	-3.0E+06	1.0E+05
DB	DBB	1.2E+04	2.6E+05	0.999	-6.2E+05	6.4E+05
	DBO	-1.4E+06	6.2E+05	0.072	-2.9E+06	1.0E+05
DBO	DBB	1.4E+06	6.3E+05	0.072	-1.0E+05	3.0E+06
	DB	1.4E+06	6.2E+05	0.072	-1.0E+05	2.9E+06

The results of this comparison reveal that the differences between all three PDMs are not significant as none are below 0.05. However, the rejection of the null hypothesis must occur, as the Brown-Forsythe value generated is indeed greater than the critical F-value for the RSD. Therefore, it must be the differences between DBB/DB and DBO CI values that drive the rejection of the null hypothesis since the significance of the difference between DBB and DB is nearly unity, indicating there is nearly no difference between these two samples. Figure B.4 reveals how the ADMs of each PDM's CI values compare to one another and confirms the findings in Table B.8.

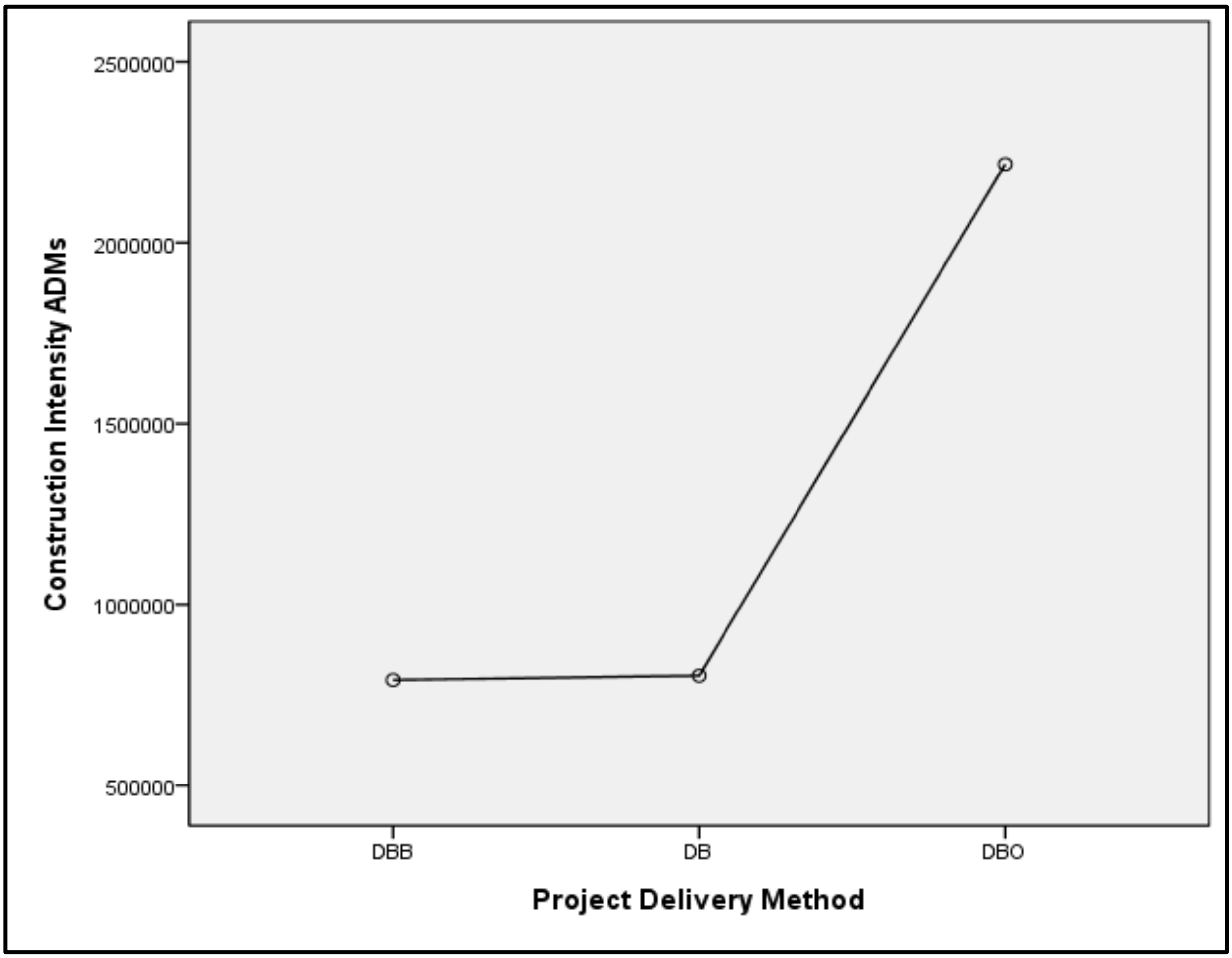

Figure B.4: Mean of the CI ADMs (Generated Using SPSS)

From the Post Hoc analysis and graph, it is clear that:

$$\sigma^2_{DBB} = \sigma^2_{DB} < \sigma^2_{DBO}$$

Because the null hypothesis was rejected, it is necessary to provide an estimate for the variability in the data sets. This is done in the "Summary and Results" section at the end of this appendix.

One Way Robust ANOVA for Central Tendency

The descriptive statistics for each PDM in conducting a One Way Robust ANOVA for central tendency are presented in Table B.9.

Table B.9: Central Tendency Descriptive Statistics for CI

Central Tendency Descriptive Statistics (CI)								
	N	Mean	Std. Dev.	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Minimum	Maximum
DBB	73	9.7E+05	1.8E+06	2.1E+05	5.6E+05	1.4E+06	1.7E+04	9.9E+06
DB	33	1.3E+06	1.2E+06	2.1E+05	8.6E+05	1.7E+06	2.3E+05	6.1E+06
DBO	38	3.2E+06	4.0E+06	6.5E+05	1.9E+06	4.5E+06	2.1E+05	2.1E+07
Total	144	1.6E+06	2.6E+06	2.2E+05	1.2E+06	2.1E+06	1.7E+04	2.1E+07

Eight-Step Test Procedure

1. Underlying Assumptions for One Way Robust ANOVA for Central Tendency:
    a. The data are continuous
    b. The data was randomly drawn from a process/population

       *In this case, the data is not a truly random sample, but rather a sample by convenience.

    c. The underlying data is *not* normally distributed
    d. The data sets compared are of *unequal* size n
2. The Test Hypotheses:

$$H_0: \mu_{DBB} = \mu_{DB} = \mu_{DBO}$$

$$H_1: \mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:

    a. F test statistic

5. Random Sampling Distribution of the Test Statistic when H_0 is True:

    a. The approximate F RSD (calculated using MVP Stats, shown as Figure B.5) when $p = 0.05$, with $J - 1$ and $n_{total} - J\ df$ where:

        i. $J = 3$, and

        ii. n_{total} equals the total number of DBB, DB, and DBO data points

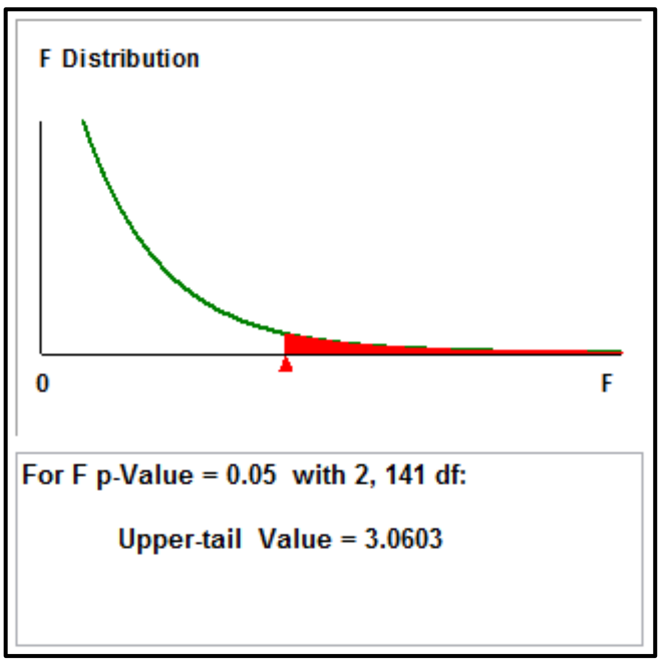

Figure B.5: F-Statistic Approximate RSD (Generated Using MVP Stats)

6. The Critical Value for Rejecting the Null Hypothesis:

Reject H_0 if F > 3.0603 and/or P –value < 0.05

7. Calculations:

   The calculations for the One Way ANOVA of central tendency were done utilizing SPSS. The results of both a Welch and Brown-Forsythe ANOVA test are presented in Table B.10. Because the Welch test is generally more conservative in comparing central tendency, the results for this test were used.

Table B.10: Robust Tests for Equality of Means

Robust Tests of Equality of Means (CI)				
	Statistic*	df1	df2	Sig.
Welch	5.3	2	72	0.007
Brown-Forsythe	8.8	2	55	0.000
*Asymptotically F Distributed				

8. Decide whether to accept or reject H_0:
   a. Decision—Reject H_0
   b. F and P-values for the Welch Test:
      i. $F = 5.3^* > 3.0603$
      ii. $P = 0.007^* < 0.05$
   c. There exists sufficient statistical evidence to infer that:

$$\mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$$

Although the null hypothesis has been rejected, this does not automatically conclude that a significant difference occurs between *all* three PDM means. In fact, the null hypothesis can be rejected in instances where there exists a large difference between only two of the three data sets. To further determine the characteristics of this significant difference, a Post-Hoc analysis was warranted. The results of this analysis are presented below in Table B.11 to individually compare and assess how the differences of each PDM's mean CI values compare to one another.

Table B.11: Post-Hoc Analysis of Central Tendency (Generated Using SPSS)

Games-Howell Multiple Comparisons (CI)						
(I) PDM	(J) PDM	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
DBB	DB	-3.1E+05	2.9E+05	0.540	-1.0E+06	3.9E+05
	DBO	-2.2E+06	6.8E+05	0.006	-3.8E+06	-5.6E+05
DB	DBB	3.1E+05	2.9E+05	0.540	-3.9E+05	1.0E+06
	DBO	-1.9E+06	6.8E+05	0.021	-3.5E+06	-2.4E+05
DBO	DBB	2.2E+06	6.8E+05	0.006	5.6E+05	3.8E+06
	DB	1.9E+06	6.8E+05	0.021	2.4E+05	3.5E+06

The results of this comparison reveal that the differences between DBO and both the DBB and DB PDMs are significant and fall below the 0.05 critical p-value. Therefore, it is the mean difference between DBB and DBO as well as DB and DBO CI that drives the rejection of the null hypothesis; not the difference between DBB and DB. Figure B.6 is a graph revealing how the means of each PDM's CI values compare to one another.

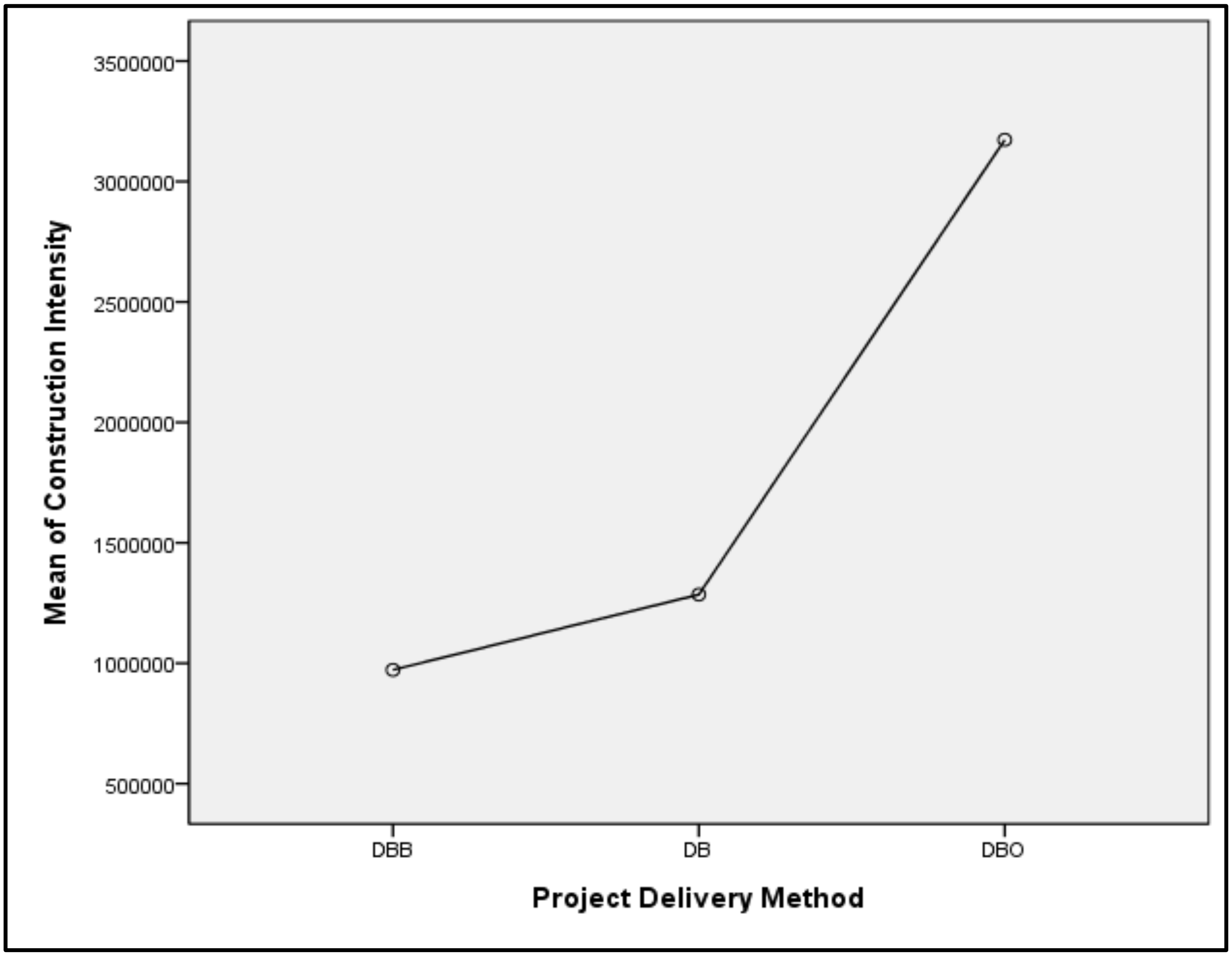

Figure B.6: Means of CI (Generated Using SPSS)

From the Post Hoc analysis and graph, it is clear that:

$$\mu_{DBB} = \mu_{DB} < \mu_{DBO}$$

Summary and Results

In conducting the analysis, it was determined that none of the sample data sets were normally distributed. Therefore, statistically speaking, it can be inferred that the underlying research populations for all data sets are not normally distributed. As a result of the data sets revealing non-normal behavior and the unequal sizes of the samples, a traditional Fischer ANOVA could not be conducted. Instead, an improved Levene test for dispersion and Welch test for central tendency were used. The finding for the ANOVA of dispersion was that the variability of DBO projects, in regards to CI, is greater than DB projects, which, in turn, is statistically equal to DBB projects. Because of this, the null hypothesis was rejected and Figures B.7, B.8 and B.9 reveal estimates for the actual variability of the data sets followed by an estimate for natural tolerance (NT).

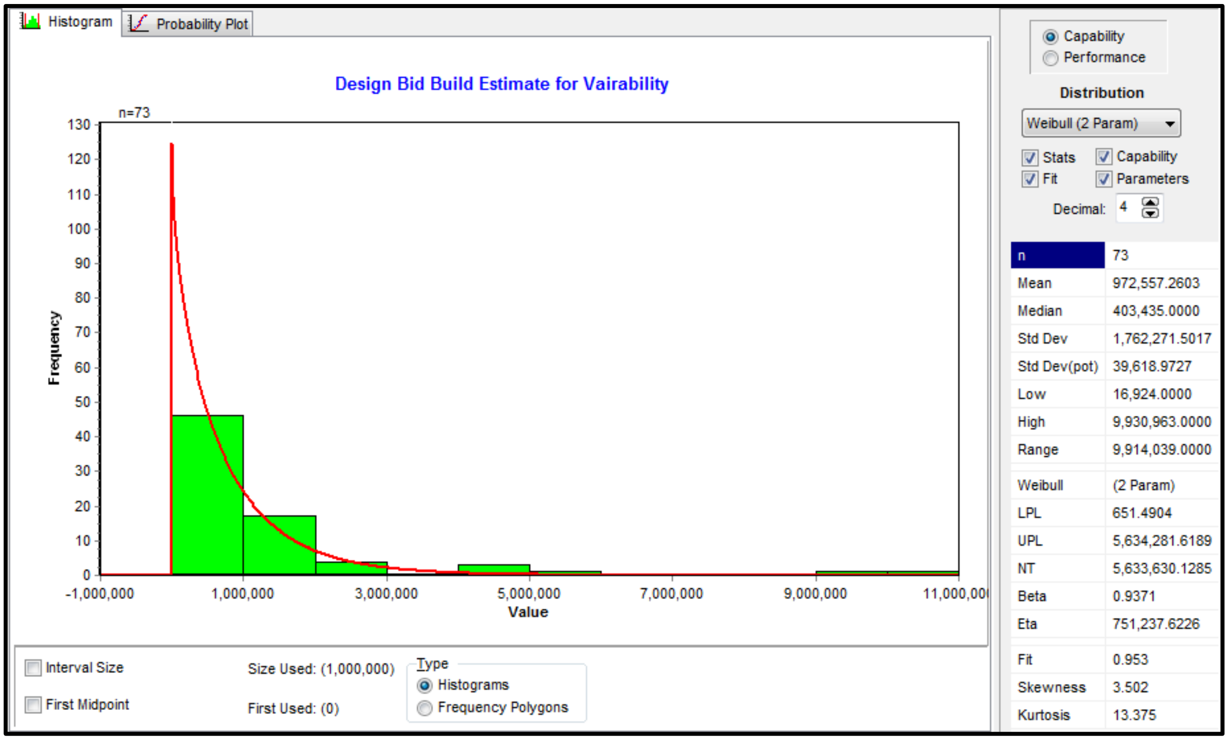

Figure B.7: DBB Estimate of Variability (Generated Using MVP Stats)

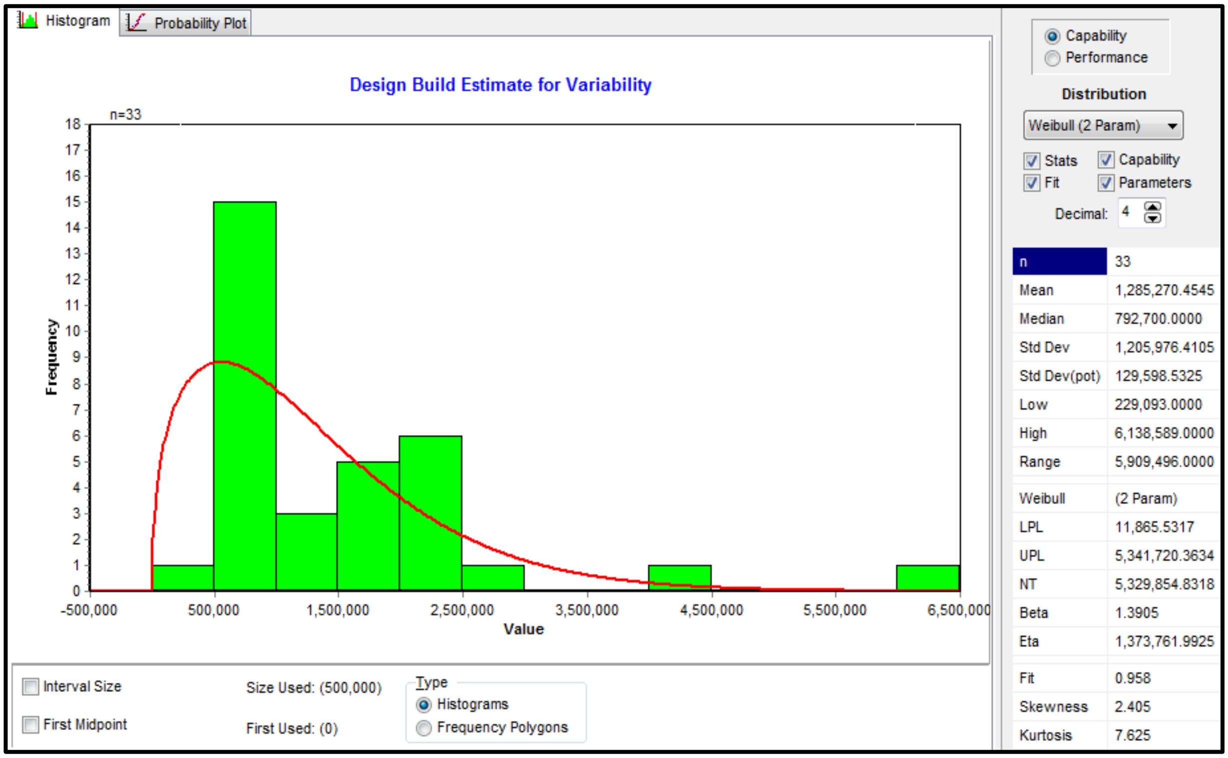

Figure B.8: DB Estimate of Variability (Generated Using MVP Stats)

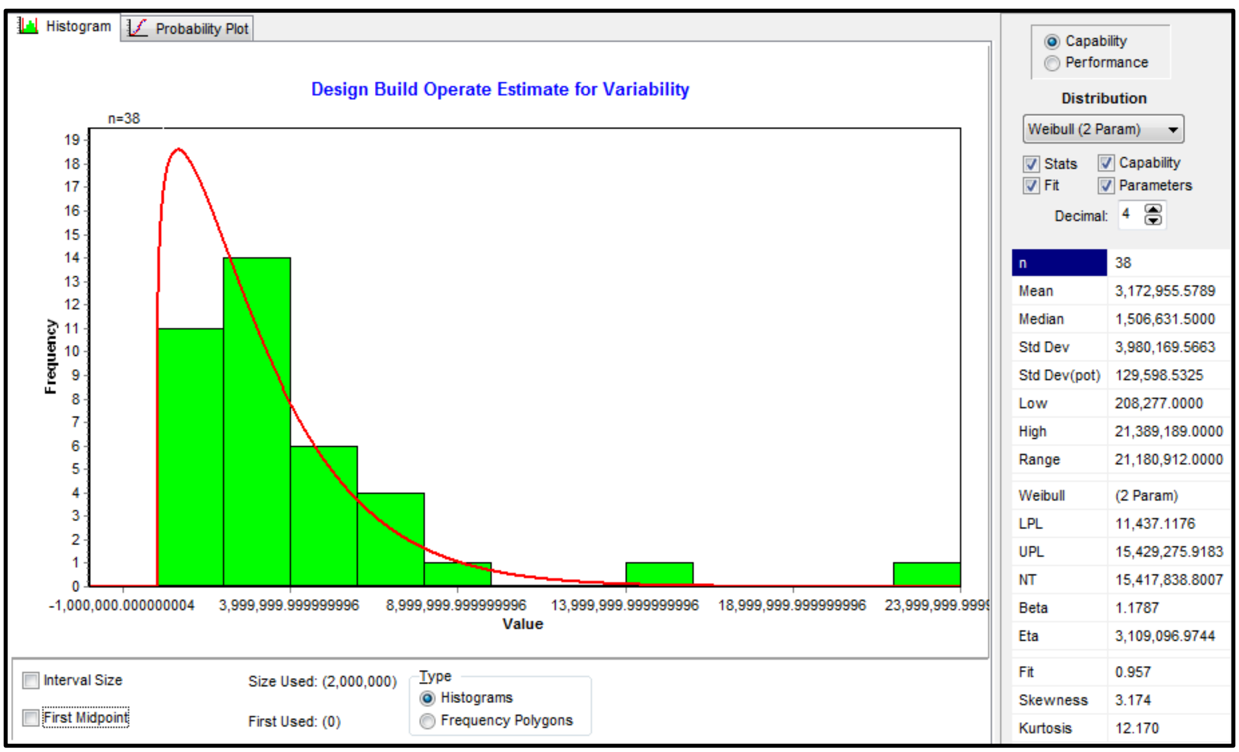

Figure B.9: DBO Estimate of Variability (Generated Using MVP Stats)

Estimate of Natural Tolerance for DBB and DB Variability:

$$NT_{DBB\ and\ DB} = \frac{(NT_{DBB} + NT_{DB})}{2} \qquad \text{Eq. (B.2)}$$

$$NT_{DBB\ and\ DB} = \frac{(5633630 + 5329854)}{2}$$

$$NT_{DBB\ and\ DB} = 5{,}500{,}000$$

Estimate of Natural Tolerance for DBO Variability:

$$NT_{DBO} = 15{,}000{,}000$$

The results of the Welch ANOVA for central tendency were that the means of CI for DBB is statistically equal to that of DB, which is less than that of DBO. Because of this, the null hypothesis was rejected and estimates for means of the data sets are as follows:

Central Tendency Estimate for DBB and DB:

$$\mu_{est\ DBB,DB} = \frac{n_{DBB}(\mu_{DBB}) + n_{DB}(\mu_{DB})}{n_{DBB} + n_{DB}} \qquad \text{Eq. (B.3)}$$

$$\mu_{est\ DBB,DB} = \frac{73(972{,}557) + 33(1{,}285{,}270)}{73 + 33}$$

$$\mu_{est\ DBB,DB} = 1{,}100{,}000\ (\$\ per\ Month)$$

Estimate for the Means of DBO:

$$\mu_{est\ DBO} = 3{,}200{,}000\ (\$\ per\ Month)$$

Calculating Importance:

When an ANOVA reveals that a statistically significant difference exists between data samples, this implies that the observed difference(s) are likely not a result of sampling error but, instead are a result of a true difference in the population parameters tested. However, this does not imply that this difference is statistically *important*. Therefore, a calculation of statistical importance is warranted. In this study, a statistically significant difference between CI means was determined to be most meaningful, and therefore, a calculation of statistical importance will be conducted for central tendency only. The equation for statistical importance (ω^2) is presented below:

$$\omega^2 = \frac{(J-1)(F-1)}{(J-1)(F-1)+J_n} \quad \text{Eq. (B.4)}$$

The following breakdown is helpful as a generalization associated with Fixed Effect ANOVAs for evaluating the importance of the statistical findings when comparing continuous data sets according to Luftig (2011):

- 70% – 100% ~ Very Important
- 50% – 69% ~ Moderate Importance
- 25% – 49% ~ Low Importance
- < 25%~ Unimportant

Using the more conservative Welch Test F-Value in calculating importance:

$$\omega_\mu^2 = \frac{(3-1)(5.3-1)}{(3-1)(5.3-1)+[(73+33+38)/3]}$$

$$\omega_\mu^2 = \frac{(2)(4.3)}{(2)(4.3)+(48)}$$

$$\omega_\mu^2 = \frac{8.6}{56.6}$$

$$\omega_\mu^2 = 15.2\%$$

Overall, an ANOVA of the CI values for each of the three PDMs has revealed that there is a statistically significant but unimportant difference in the means of these values for DBB, DB, and DBO delivery. The mean CI value of DBO projects is much higher than DBB and DB projects at an estimated \$3,200,000/month. The mean CI value for DB is statistically equal to DBB, but lower than DBO at an aggregated estimate value of \$1,100,000/month.

APPENDIX C

DATA ANALYSIS III: 5M-50M USD PROJECTS

Introduction

This data analysis is performed on only the data corresponding to capital costs in the range of five million to 50 million USD. This range of hard costs corresponds to the majority of data points collected for every sample. It was determined that analyzing data with similar hard costs would reveal interesting findings regarding CI since holding hard costs in a constant range of values allows the duration of each project to be the driving force for increasing and decreasing CI. In turn, this forces the results to be more reflective of the ability of each PDM to *compress a project schedule*, a characteristic more indicative of an integrated PDM.

Describing the Data Sets

The total number of data points for this analysis is as follows:

- DBB: 41 data points
- DB: 21 data points
- DBO: 20 data points

Table C.1 reveals the D&C duration data for each sample set.

Table C.1: Design and Construction Duration Data

Design and Construction Duration (Months)				
	DBB	DB	DBO	Units
Data Pts.	41	21	20	
Mean	38	21	26	Months
Median	36	18	26	Months
Mode	36	-	24	Months
Range	84	43	31	Months
Std. Dev.	18	11	7	Months
High	96	48	42	Months
Low	12	5	11	Months

From the table, DBB projects are shown to have, on average, a 200% longer D&C schedule durations than their DB and DBO counterparts. There is not a single DBB project in the cleaned data set that was completed in less than one year. Additionally, the largest D&C duration is found in a DBB project. DB projects showed the lowest average for duration values across all three data sets even though the range of duration data is similar for DB and DBO projects. This may be due to larger projects being constructed using the DBO PDM than DB PDM, since both overlap design and construction phases and compress the project schedule in a similar manner.

Table C.2 presents the D&C hard cost data used in this analysis, and Figure C.1 is a graph representing the D&C capital cost data across all three PDM data samples.

Table C.2: Design and Construction Hard Cost Data

Design and Construction Hard Cost (2010 USD)			
	DBB	**DB**	**DBO**
Data Pts.	41	21	20
Average	$18,000,000	$15,000,000	$28,000,000
Median	$12,000,000	$11,000,000	$27,000,000
Mode	-	-	-
Range	$45,000,000	$37,000,000	$40,000,000
Std. Dev.	$13,000,000	$9,600,000	$11,000,000
High	$50,000,000	$42,000,000	$47,000,000
Low	$5,100,000	$5,700,000	$7,400,000

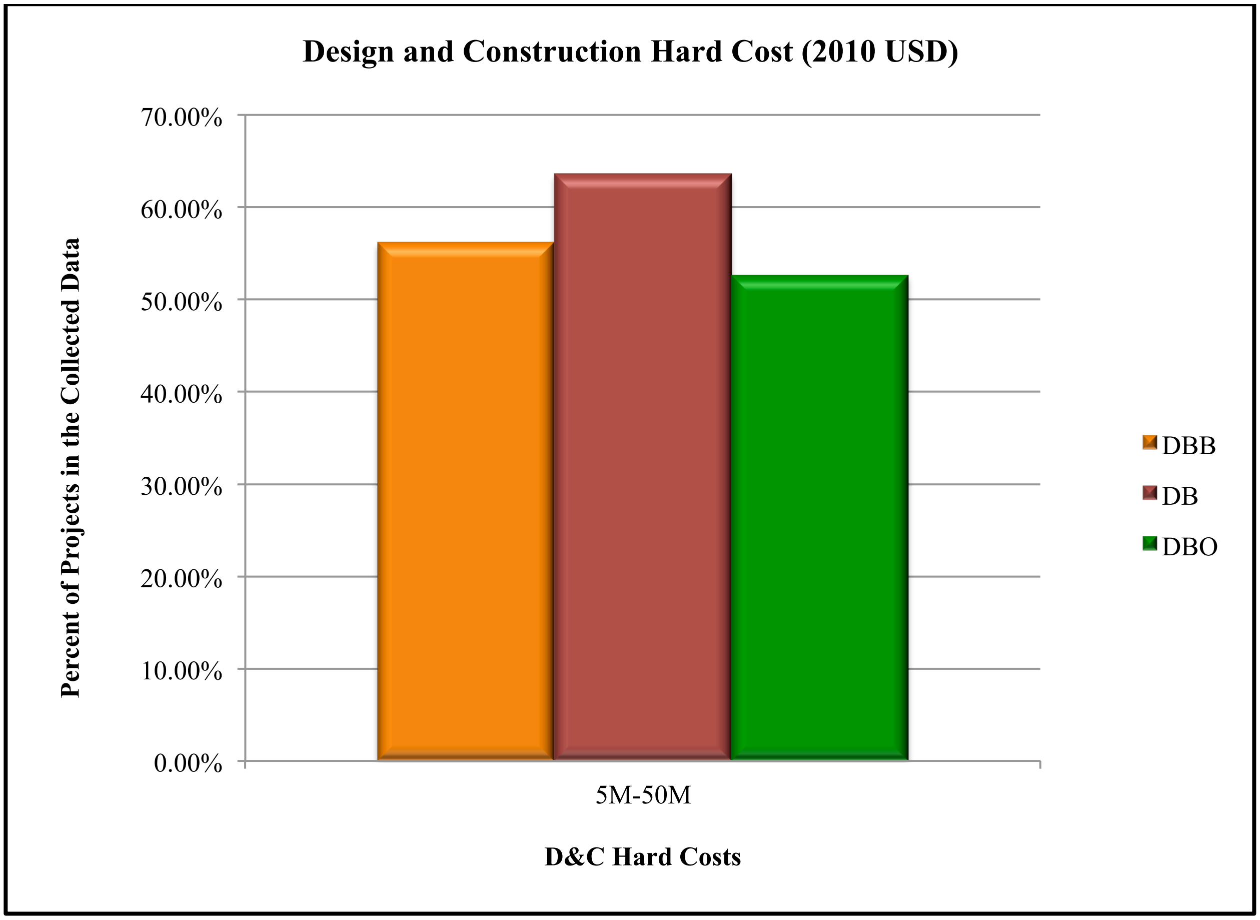

Figure C.1: Design and Construction Hard Costs

The hard costs are comparable since all were brought to 2010 present values using Engineering News Records (ENR) Construction Cost Indices (CCI). To normalize the cost data, the annual CCI from ENR (2011) was used in the following manner:

$$D\&C\ Hard\ Costs\ (2010\ USD) = \frac{D\&C\ Hard\ Cost}{CCI\ (Design\ Year)} * CCI\ (Year\ 2010) \qquad \text{Eq. (C.1)}$$

All cost data was normalized from the year design began. Table C.2 reveals that, on average, the capital costs for the DBO data is nearly 155% greater than that for DBB projects. Additionally, DBB projects, on average, exhibit higher hard costs for D&C than did DB by nearly 120%. Moreover, the median for DBO data is much greater than the medians for DBB and DB.

Table C.3 presents the CI data for each PDM sample set, and Figure C.2 is a scatter plot of the CI values for each PDM.

Table C.3: Construction Intensity Data

Construction Intensity (2010 USD/Month)			
	DBB	DB	DBO
Data Pts.	41	21	20
Average	$510,000	$850,000	$1,100,000
Median	$440,000	$600,000	$1,100,000
Mode	-	-	-
Range	$1,900,000	$1,800,000	$2,200,000
Std. Dev.	$400,000	$530,000	$470,000
High	$2,000,000	$2,200,000	$2,600,000
Low	$100,000	$310,000	$410,000

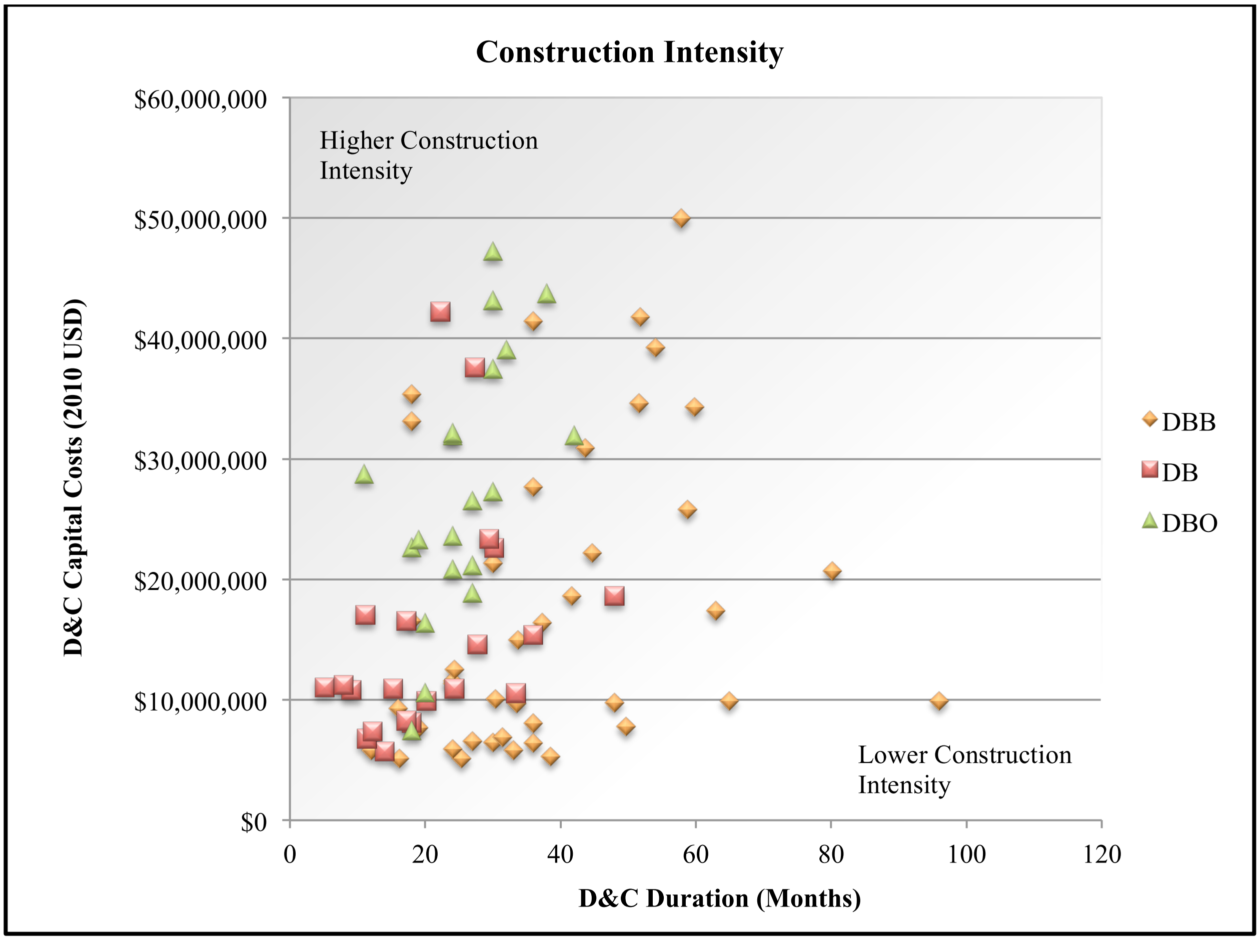

Figure C.2: Construction Intensity Data

Overall, DBO projects exhibit a greater degree of CI, on average, over their DBB and DB project counterparts. This difference is nearly 215% greater when compared the DBB PDM and 129% greater when compared to DB PDM. Moreover, DB projects also exhibit a significantly greater degree of CI over DBB projects by nearly 166%. The medians of each data represent similar rankings as the averages. The DBO median for CI is 183% greater than the DB median and 250% greater than the DBB median.

Research Variables

The measurable variables for this investigation were both quantitative and qualitative. The quantitative parameters were: 1) D&C duration quantified by months; and 2) D&C hard costs normalized to 2010 USD. The degree of delivery integration represented the qualitative variable. Previous research by John B. Miller and the ISDR at MIT group coded PDMs using this degree as a parameter of classification. The findings from these research efforts were considered comprehensive, and therefore, were applied here.

The dependent research variable for this research was CI. The criterion measure for CI was D&C hard costs per D&C duration. The CI variable was considered underlying continuous, ratio data. Conversely, the independent research variable was the PDM level of integration classified by Miller et. al. (2000). This variable was measured quantitatively and was considered nominal data.

Table C.4 presents the descriptive statistics for the three data samples compared in the ANOVA.

Table C.4: Descriptive Statistics for the Data Samples

Descriptive Statistics						
PDM	N	Mean	Std. Dev.	Low	High	Range
(All)	82	7.4E+05	5.2E+05	1.0E+05	2.6E+06	2.5E+06
1	41	5.1E+05	4.0E+05	1.0E+05	2.0E+06	1.9E+06
2	21	8.5E+05	5.3E+05	3.1E+05	2.2E+06	1.8E+06
3	20	1.1E+06	4.7E+05	4.1E+05	2.6E+06	2.2E+06

Overview and Statistical Hypotheses

In order to answer the research question, the following statistical hypothesis must be answered and tested in the following order:

Shape: Test for Normality

For the Moment Test on data sets with $n > 25$

$$H_0: \gamma 3 = 0.00 \qquad H_1: \gamma 3 \neq 0.00$$

$$H_0: \gamma 4 = 0.00 \qquad H_1: \gamma 4 \neq 0.00$$

For the Anderson-Darling Test on data sets with $n \leq 25$

$$H_0: A\text{-}D \leq 0.752 \qquad H_1: A\text{-}D > 0.752$$

It is important to note that normality will be tested for the project data within each of the three PDM data sets individually, not in aggregate.

Spread: Test for Dispersion

$$H_0: \sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$$

$$H_1: \sigma^2_{DBB} \neq \sigma^2_{DB} \neq \sigma^2_{DBO}$$

Location: Test for the Equality of Means

$$H_0: \mu_{DBB} = \mu_{DB} = \mu_{DBO}$$

$$H_1: \mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$$

Determining the Underlying Shape of the Research Population: Testing for Normality

When sample sizes are less than 25, the appropriate test for normality is the Anderson-Darling Test. When sample sizes are greater than 25, the appropriate tests for normality are the moment tests in which skewness and kurtosis are tested separately. In this analysis, the sample size for the DBB PDM is greater than 25, and therefore, the moment tests were used to test normality. However, the sample sizes for the DB and DBO data sets are less than 25, and will be tested using the Anderson-Darling Test for normality. The following eight-step procedure is performed for all three data sets simultaneously, as the results and procedure itself are similar for each.

Eight-Step Statistical Hypothesis Test Procedure for Normality

1. Underlying Assumptions of the Test For Normality:
    a. The data are continuous
    b. The data was randomly drawn from a process/population.

       *In this case, the data is not a truly random sample, but rather a sample by convenience.
2. The Test Hypotheses:

$$H_0: \gamma_3 = 0.00 \qquad H_1: \gamma_3 \neq 0.00$$

$$H_0: \gamma_4 = 0.00 \qquad H_1: \gamma_4 \neq 0.00$$

$$H_0: \text{A-D} \leq 0.752 \qquad H_1: \text{A-D} > 0.752$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:
    a. For moment tests:
        i. Skewness—t statistic
        ii. Kurtosis—standard table values for kurtosis
    b. For the Anderson-Darling Test:
        i. A-D value ≤ 0.752
5. Random Sampling Distribution of the Test Statistic when H_0 is True:
    a. For moment tests

i. Skewness—t-statistic (Approximate)

ii. Kurtosis—simulated or normal (Approximate)

b. For the Anderson-Darling Test

i. A-D Test—Cramér-von-Mises criterion

6. The Critical Value for Rejecting the Null Hypothesis:

Reject H_0 if p-value < 0.05

7. Calculations:

The calculations for normality were done using the MVP stats software. The results of these computations are presented below in Table C.5. The yellow highlights denote p-values below identified level of risk acceptance.

Table C.5: Testing for Normality

Normality Tests							
PDM	**N**	**A-D**	**p-value**	**Skewness**	**p-value**	**Kurtosis**	**p-value**
(All)	82	2.5	0.000*	1.3	0.000*	1.6	.10-.05
1	41	N/A	N/A	2.2	0.000*	5.5	<0.02*
2	21	1.4	0.001*	N/A	N/A	N/A	N/A
3	20	0.70	0.067	N/A	N/A	N/A	N/A

8. Decide whether to accept or reject H_0:

a. Decisions:

i. Reject H_0 for DBB data set

ii. Reject H_0 for DB data set

iii. Accept H_0 for DBO data set

b. P-values:

i. P-values for DBB data set: ≈ 0.000* and <0.02*

ii. P-value for DB data set: ≈ 0.001*

iii. P-value for DBO data set: ≈ 0.067

c. There exists sufficient statistical evidence to infer that the DBB and DB data sets are not normally distributed. Therefore, the underlying research population can also be inferred to not follow a normal distribution for these PDMs. However, the DBO data set was found to statistically behave under the characteristics of a normal distribution.

d. Estimate of shape: Using the MVP stats histogram generation program, the distribution found to best fit the DBB and DB data sets is as follows:

   i. Gamma (0) distribution for DBB data with a fit of 0.985

   ii. Gamma (0) distribution for DB data with a fit of 0.942

From the normality tests, it is clear that two of the data sets are *not* normally distributed and the number of data points in each set is not equal. Because of this, a traditional Fischer One Way ANOVA is not applicable. Therefore, Leven's Improved Test (Brown-Forsythe Test) for Dispersion, and a Welch test for central tendency were used.

Levene's Improved Test (Brown-Forsythe Test) for Dispersion

In order to conduct a Levene's improved test for dispersion on data that is not normally distributed and between sample sets of unequal size n, the ADMs for all three groups must first be computed. Doing so has been shown to significantly increase the effectiveness of the test (Luftig, 2011). These absolute values can then be compared using an ANOVA. The ADMs were found utilizing the MVP stats software. After calculating the ADMs, these data were transferred into SPSS to conduct the comparison analysis. The descriptive statistics for each PDM are presented in Table C.6

Table C.6: Dispersion Descriptive Statistics for CI

Dispersion ADM Descriptive Statistics (CI)								
	N	Mean	Std. Dev.	Std. Error	95% Confidence Interval		Minimum	Maximum
					Lower Bound	Upper Bound		
DBB	41	2.6E+05	3.1E+05	4.8E+04	1.7E+05	3.6E+05	0.0E+00	1.5E+06
DB	21	3.9E+05	4.3E+05	9.4E+04	2.0E+05	5.9E+05	0.0E+00	1.6E+06
DBO	20	3.3E+05	3.3E+05	7.3E+04	1.8E+05	4.9E+05	8.4E+04	1.5E+06
Total	82	3.1E+05	3.5E+05	3.8E+04	2.4E+05	3.9E+05	0.0E+00	1.6E+06

Eight-Step Test Procedure

1. Underlying Assumptions for Levene's Improved Test for Dispersion:

    a. The data are continuous

    b. The data was randomly drawn from a process/population

    *In this case, the data is not a truly random sample, but rather a sample by convenience.

    c. The underlying data is *not* normally distributed

    d. The data sets compared are of *unequal* size n

2. The Test Hypotheses:

$$H_0: \sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$$

$$H_1: \sigma^2_{DBB} \neq \sigma^2_{DB} \neq \sigma^2_{DBO}$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:

    a. F test statistic

5. Random Sampling Distribution of the Test Statistic when H_0 is True:

    a. The approximate F-statistic RSD (calculated using MVP Stats, shown as Figure C.3) when $p = 0.05$, with $J - 1$ and $n_{total} - J\ df$ where:

        i. $J = 3$, and

ii. n_{total} equals the total number of DBB, DB, and DBO data points

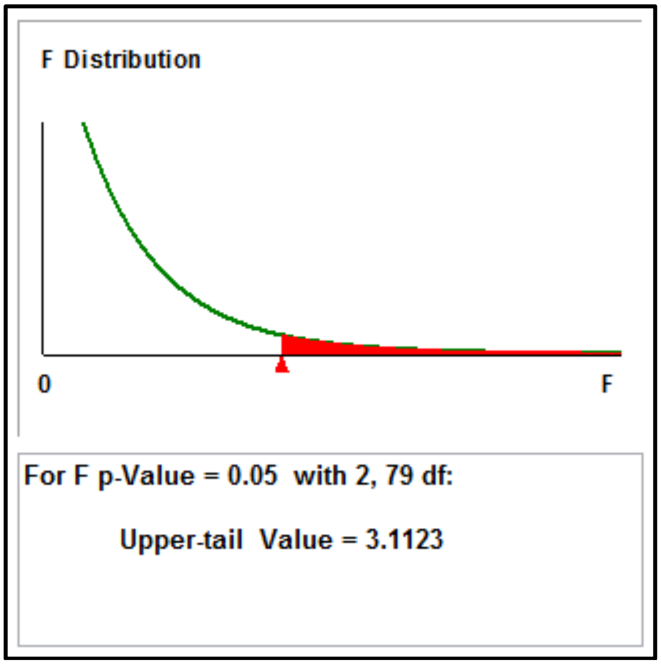

Figure C.3: F-Statistic Approximate RSD (Generated Using MVP Stats)

6. The Critical Value for Rejecting the Null Hypothesis:

Reject H_0 if $F > 3.1123$ and/or P-value < 0.05

7. Calculations:

The calculations for dispersion were done utilizing both MVP stats to generate the ADMs and SPSS to perform the ANOVA. The results of the Brown-Forsythe ANOVA test on the ADMs for the three PDM sample sets are presented in Table C.7.

Table C.7: Robust Test for Equality of Dispersion

Robust Tests for Equality of Means (CI)				
	Statistic*	df1	df2	Sig.
Welch	0.83	2	39	0.44
Brown-Forsythe	0.88	2	52	0.42

*Asymptotically F Distributed

8. Decide whether to accept or reject H_0:

   a. Decisions—Accept H_0

   b. F and P-values for the Brown-Forsythe Test:

i. $F = 0.88 < 3.0603$

ii. $P = 0.42 > 0.05$

c. There exists sufficient statistical evidence to infer that:

$$\sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$$

Figure C.4 reveals a graph of the mean values for the variances for each PDM.

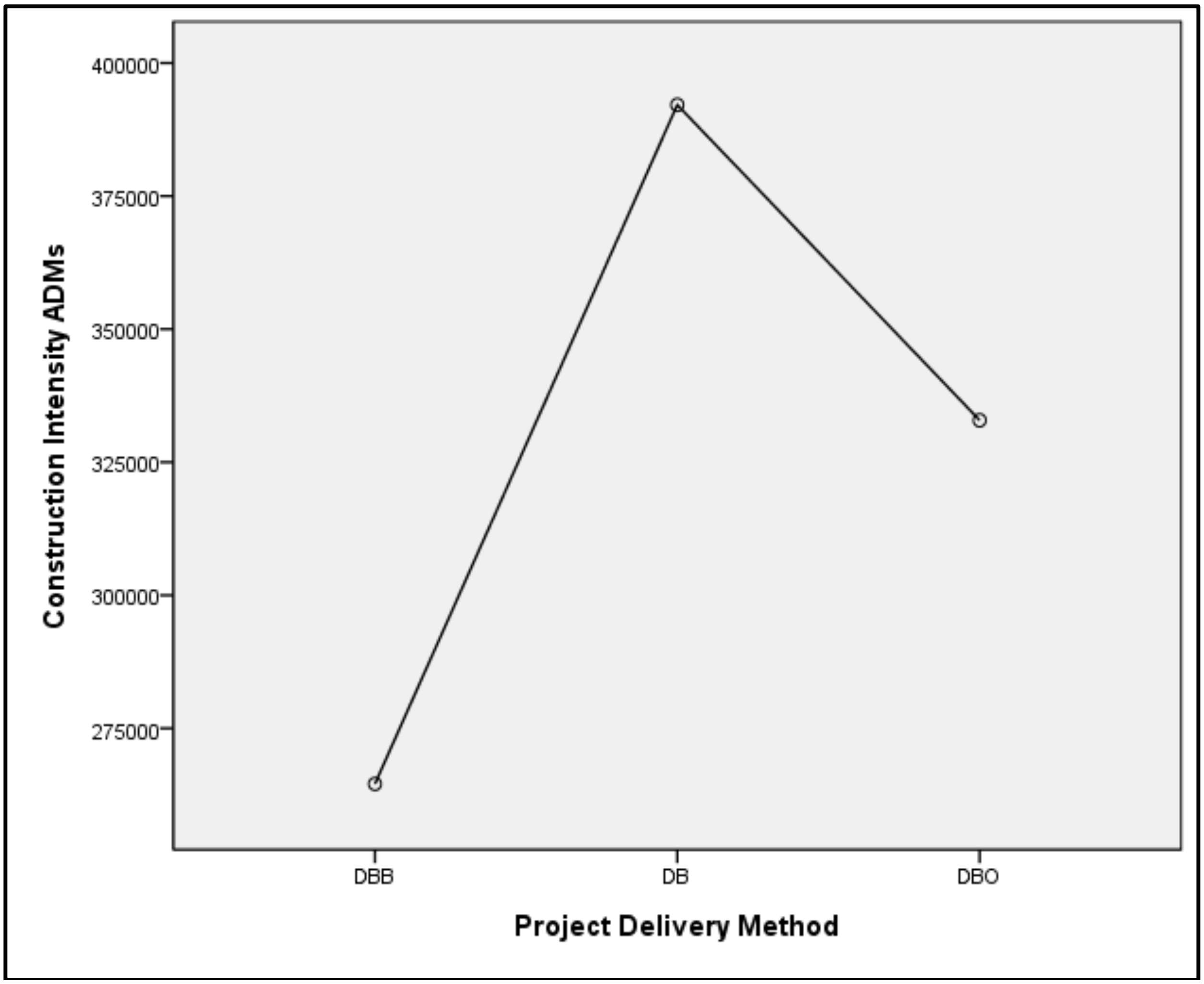

Figure C.4: Mean of the CI ADMs (Generated Using SPSS)

From the analysis and Figure C.4, it can be inferred that:

$$\sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$$

Because the null hypothesis was accepted, it is not necessary to provide an estimate for the variability in the data sets.

One Way Robust ANOVA for Central Tendency

The descriptive statistics for each PDM in conducting a One Way Robust ANOVA for central tendency are presented in Table C.8.

Table C.8: Central Tendency Descriptive Statistics for CI

Central Tendency Descriptive Statistics (CI)								
	N	Mean	Std. Dev.	Std. Error	95% Confidence Interval		Minimum	Maximum
					Lower Bound	Upper Bound		
DBB	41	5.1E+05	4.0E+05	6.3E+04	3.8E+05	6.4E+05	1.0E+05	2.0E+06
DB	21	8.5E+05	5.3E+05	1.2E+05	6.1E+05	1.1E+06	3.1E+05	2.2E+06
DBO	20	1.1E+06	4.7E+05	1.1E+05	8.9E+05	1.3E+06	4.1E+05	2.6E+06
Total	82	7.4E+05	5.2E+05	5.7E+04	6.3E+05	8.6E+05	1.0E+05	2.6E+06

Eight-Step Test Procedure

1. Underlying Assumptions for One Way Robust ANOVA for Central Tendency:
    a. The data are continuous
    b. The data was randomly drawn from a process/population

       *In this case, the data is not a truly random sample, but rather a sample by convenience.
    c. The underlying data is *not* normally distributed
    d. The data sets compared are of *unequal* size n
2. The Test Hypotheses:

$$H_0: \mu_{DBB} = \mu_{DB} = \mu_{DBO}$$

$$H_1: \mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$$

3. The Maximum Risk Acceptance For Committing a Type I (Alpha) Error:

$$\alpha = 0.05$$

4. The Associated Test Statistic:

    a. F test statistic

5. Random Sampling Distribution of the Test Statistic when H_0 is True:

    d. The approximate F RSD (calculated using MVP Stats, shown as Figure C.5) when $p = 0.05$, with $J - 1$ and $n_{total} - J\ df$ where:

        i. $J = 3$, and

        ii. n_{total} equals the total number of DBB, DB, and DBO data points

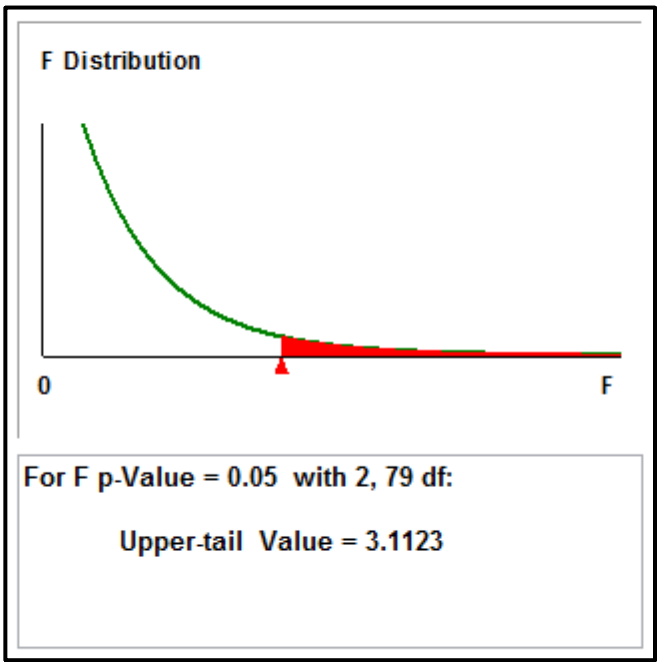

Figure C.5: F-Statistic Approximate RSD (Generated Using MVP Stats)

6. The Critical Value for Rejecting the Null Hypothesis:

$$\text{Reject } H_0 \text{ if } F > 3.1123 \text{ and/or P-value} < 0.05$$

7. Calculations:

The calculations for the One Way ANOVA of central tendency were done utilizing SPSS. The results of both a Welch and Brown-Forsythe ANOVA test are presented in Table

C.9. Because the Welch test is generally more conservative in comparing central tendency, the results for this test were used in this analysis.

Table C.9: Robust Tests for Equality of Means

Robust Tests for Equality of Means (CI)				
	Statistic*	df1	df2	Sig.
Welch	13	2	38	0.000
Brown-Forsythe	11	2	55	0.000

*Asymptotically F Distributed

8. Decide whether to accept or reject H_0:

    a. Decisions—Reject H_0

    b. F and P-values for the Welch Test:

        i. $F = 13^* > 3.0603$

        ii. $P = 0.000^* < 0.05$

    c. There exists sufficient statistical evidence to infer that:

$$\mu_{DBB} \neq \mu_{DB} \neq \mu_{DBO}$$

Although the null hypothesis has been rejected, this does not automatically conclude that a significant difference occurs between *all* three PDM means. In fact, the null hypothesis can be rejected in instances where there exists a large difference between only two of the three data sets. To further determine the characteristics of this significant difference, a Post-Hoc analysis was warranted. The results of this analysis are presented below in Table C.10 to individually compare and assess how the differences of each PDM's mean CI values compare to one another.

Table C.10: Post-Hoc Analysis of Central Tendency (Generated Using SPSS)

Games-Howell Multiple Comparisons (CI)						
(I) PDM	(J) PDM	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
DBB	DB	-3.4E+05	1.3E+05	0.036	-6.7E+05	-1.9E+04
	DBO	-6.0E+05	1.2E+05	0.000	-9.0E+05	-3.0E+05
DB	DBB	3.4E+05	1.3E+05	0.036	1.9E+04	6.7E+05
	DBO	-2.6E+05	1.6E+05	0.245	-6.4E+05	1.3E+05
DBO	DBB	6.0E+05	1.2E+05	0.000	3.0E+05	9.0E+05
	DB	2.6E+05	1.6E+05	0.245	-1.3E+05	6.4E+05

The results of this comparison reveal that the differences between DBO and both the DBB and DB PDMs are significant and fall below the 0.05 critical p-value. Additionally, the difference between DB and DBB is also significant and falls below the 0.05 critical value. Therefore, the mean differences between *all* PDM samples sets are contributing to the rejection of the null hypothesis. Figure C.6 is a graph revealing how the means of each PDM's CI values compare to one another.

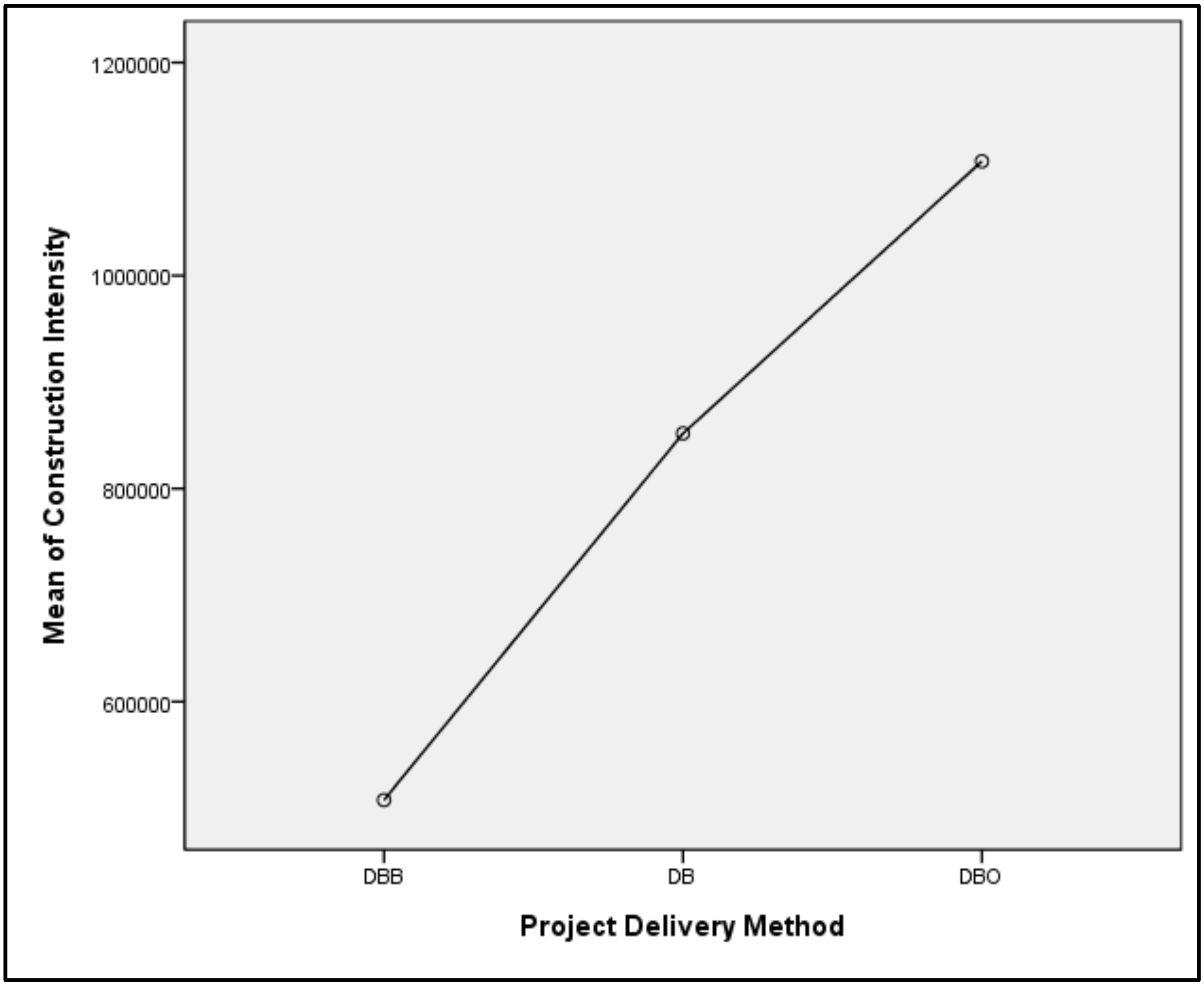

Figure C.6: Mean of CI (Generated Using SPSS)

From the Post Hoc analysis and graph, it is clear that:

$$\mu_{DBB} < \mu_{DB} < \mu_{DBO}$$

Summary and Results

In conducting the analysis, it was determined that only the DBO sample data set is normally distributed. The DBB and DB data sets were shown to exhibit non-normal behavior. As a result of this and the unequal sizes of the PDM samples, a traditional Fischer ANOVA could not be conducted. Instead, an improved Levene test for dispersion and Welch test for central tendency were used. The finding for the ANOVA for dispersion was that the null hypothesis should be accepted and that the means of the variability between all three PDM data sets, in regards to CI, are statistically equal.

The results of the Welch ANOVA for central tendency were that the mean value of CI for DBB is statistically less than that of DB, which, in turn, is less than that of DBO. Because of this, the null hypothesis was rejected and the estimates for means of the data sets are as follows:

$$\mu_{est\ DBB} = 510{,}000\ (\$\ per\ Month)$$

$$\mu_{est\ DB} = 850{,}000\ (\$\ per\ Month)$$

$$\mu_{est\ DBO} = 1{,}100{,}000\ (\$\ per\ Month)$$

Calculating Importance:

When an ANOVA reveals that a statistically significant difference exists between data samples, this implies that the observed difference(s) are likely not a result of sampling error but, instead are a result of a true difference in the population parameters tested. However, this does not imply that this difference is statistically *important*. Therefore, a calculation of statistical importance is warranted. In this study, a statistically significant difference between CI means was determined to be most meaningful, and therefore, a calculation of statistical importance will be conducted for central tendency only. The equation for statistical importance (ω^2) is presented below:

$$\omega^2 = \frac{(J-1)(F-1)}{(J-1)(F-1)+J_n} \qquad \text{Eq. (C.2)}$$

The following breakdown is helpful as a generalization associated with Fixed Effect ANOVAs for evaluating the importance of the statistical findings when comparing continuous data sets according to Luftig (2011):

- 70% – 100% ~ Very Important
- 50% – 69% ~ Moderate Importance

- 25% – 49% ~ Low Importance
- < 25%~ Unimportant

Using the more conservative Welch Test F-Value in calculating importance:

$$\omega_\mu^2 = \frac{(3-1)(13-1)}{(3-1)(13-1) + [(41+21+20)/3]}$$

$$\omega_\mu^2 = \frac{(2)(12)}{(2)(12) + (27.33)}$$

$$\omega_\mu^2 = \frac{8.6}{56.6}$$

$$\omega_\mu^2 = 46.8\%$$

Overall, an ANOVA of the CI values for each of the three PDMs has revealed that there is a statistically significant and low important difference in the means of these values for the DBB, DB, and DBO PDMs. The mean CI value for DBO projects is much higher than DBB and DB projects at an estimate of $1,100,000/month. The mean CI value for DBB and DB projects are $510,000/month and $850,000/month respectively.

APPENDIX D

Data Analysis Results Table

Table D.1: Summary Table for Data Analyses

Data Analyses Results Table				
Statistical Test	**Null Hypotheses**	**A/R**	**Result/p-values**	**Estimates (If Null is Rejected)**
Analysis I: Cleaned Data				
DBB Data Test for Normality	H_0: $\gamma 3 = 0.00$ H_0: $\gamma 4 = 0.00$	Reject Accept	0.011 > 0.10	Gamma (0) Distribution
DB Data Test for Normality	H_0: $\gamma 3 = 0.00$ H_0: $\gamma 4 = 0.00$	Accept Accept	0.249 > 0.10	Normal Distribution
DBO Data Test for Normality	H_0: $\gamma 3 = 0.00$ H_0: $\gamma 4 = 0.00$	Reject Reject	0.014 > 0.10	Gamma (0) Distribution
Levene's Improved Test for Dispersion	H_0: $\sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$	Reject	$\sigma^2_{DBB} < \sigma^2_{DB} < \sigma^2_{DBO}$	DBB NT = 2,100,000 DB NT = 4,100,000 DBO NT = 11,000,000
Welch Test for Central Tendency	H_0: $\mu_{DBB} = \mu_{DB} = \mu_{DBO}$	Reject	$\mu_{DBB} < \mu_{DB} < \mu_{DBO}$	μ_{DBB} = 520,000 μ_{DB} = 1,100,000 μ_{DBO} = 2,300,000
Importance/Significance of Finding			57.6%	Moderate Importance
Analysis II: All Collected Data				
DBB Data Test for Normality	H_0: $\gamma 3 = 0.00$ H_0: $\gamma 4 = 0.00$	Reject Reject	0.000 <0.02	Two-Parameter Weibull Distribution
DB Data Test for Normality	H_0: $\gamma 3 = 0.00$ H_0: $\gamma 4 = 0.00$	Reject Reject	0.000 <0.02	Two-Parameter Weibull Distribution
DBO Data Test for Normality	H_0: $\gamma 3 = 0.00$ H_0: $\gamma 4 = 0.00$	Reject Reject	0.000 <0.02	Two-Parameter Weibull Distribution
Levene's Improved Test for Dispersion	H_0: $\sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$	Reject	$\sigma^2_{DBB} = \sigma^2_{DB} < \sigma^2_{DBO}$	DBB and DB NT = 5,500,000 DBO NT = 15,000,000
Welch Test for Central Tendency	H_0: $\mu_{DBB} = \mu_{DB} = \mu_{DBO}$	Reject	$\mu_{DBB} = \mu_{DB} < \mu_{DBO}$	μ_{DBB} and μ_{DB} = 1,100,000 ($/Mo.) μ_{DBO} = 3,200,000 ($/Mo.)
Importance/Significance of Finding			15.2%	Unimportant
Analysis III: $5 million to $50 million Data				
DBB Data Test for Normality	H_0: $\gamma 3 = 0.00$ H_0: $\gamma 4 = 0.00$	Reject Reject	0.000 <0.02	Gamma (0) Distribution
DB Data Test for Normality	H_0: A-D $\leq$ 0.752	Reject	0.000	Gamma (0) Distribution
DBO Data Test for Normality	H_0: A-D $\leq$ 0.752	Accept	0.067	Normal Distribution
Levene's Improved Test for Dispersion	H_0: $\sigma^2_{DBB} = \sigma^2_{DB} = \sigma^2_{DBO}$	Accept	0.42	N/A
Welch Test for Central Tendency	H_0: $\mu_{DBB} = \mu_{DB} = \mu_{DBO}$	Reject	$\mu_{DBB} < \mu_{DB} < \mu_{DBO}$	μ_{DBB} = 510,000 ($/Mo.) μ_{DB} = 850,000 ($/Mo.) μ_{DBO} = 1,100,000 ($/Mo.)
Importance/Significance of Finding			46.8%	Low Importance