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Using Robust Statistical Methodology to Evaluate the Cost Performance of Project Delivery Systems: A Case Study of Horizontal Construction

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The objective of this study is to demonstrate the application of the bootstrapping M-estimator (a robust analysis of variance [ANOVA]) to test the null hypothesis of means equality among the cost performance of the three project delivery systems (PDS). A statistical planned contrast methodology is utilized after the robust ANOVA analysis to further determine where the differences of the means lie. The results of this research concluded that traditional PDS (Design-Bid-Build [DBB]) outperformed the two innovative PDS (Design-Build [DB] and Construction Manager/General Contractor [CMGC]), DBB and CMGC outperformed DB, and DBB outperformed CMGC, for the Cost Growth and the Change Order Cost Factor performance. These findings can help decision makers/owners make an informed decision regarding cost related aspects when choosing PDS for their projects. Though the case study of this research is based on the sample data obtained from the construction industry, the same methodology and statistical process can be applied to other industries and factors/variables of interest when the study sample data are unbalanced and the normality and homogeneity of variance assumptions are violated.

Introduction

This research article is a study of the performance comparison of the three project delivery systems (PDS) with respect to the Cost Growth and the Change Order Cost Factor of the horizontal construction. The three PDS under this study are: Design-Bid-Build (DBB), Design-Build (DB), and Construction Manager/General Contractor (CMGC). The DBB methodology is the construction industry's traditional PDS (Sanvido & Konchar, 1998). The DB and the CMGC methodologies are the two popular alternative PDS to the traditional DBB methodology (Rojas & Kell, 2008).

Problem Statement and Background

In general, there are two types of construction classified in the construction industry: vertical and horizontal construction (Brenner & Brenner, 2015). The vertical construction involves buildings whereas horizontal construction involves bridge and roadway

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infrastructure. The horizontal construction industry was chosen for this study because its performance of DBB, DB, and CMGC with regard to the Cost Growth and the Change Order Cost Factor has not yet empirically been compared simultaneously. The lack of study of the performance comparison of the three PDS in the horizontal construction industry is most likely due in part to the infancy of the DB and the CMGC (with CMGC in particular). The CMGC methodology is the horizontal construction industry's new interest. It has been used in complex vertical construction for decades. This has recently been introduced to the horizontal, i.e., transportation, infrastructure industry (Anderson & Damnjanovic, 2008).

The delay in the introduction and use of the DB and the CMGC methodologies to the horizontal construction industry relative to its use for decades in complex vertical construction is due to state laws and regulations. Ghavamifar and Touran (2008) discussed the uses and involvements of laws and limitations of the two PDS (DB and CMGC) in the horizontal (transportation) projects. They categorized the authority of using project delivery systems into four categories based on statutory permission for the transportation projects. The four categories ranged from "fully authorized" to "not authorized."

There have been many investigations of the PDS performance between DBB and DB methodologies in the vertical construction industry (e.g., Fernane, 2011; Hale, Shrestha, Gibson, & Migliaccio, 2009; Ibbs, Kwak, Ng, & Odabasi, 2003; Rosner, Thal, & West, 2009); quite a few studies comparing DBB and CMGC (e.g., Carpenter, 2014); Rojas & Kell, 2008; Septelka & Goldblatt, 2005; Williams, 2003); and also studies comparing CMGC and DB (e.g., Maharjan, 2013; Shrestha, Maharjan, Shakya, & Batista, 2014). Carpenter (2014) claimed that the most frequently cited study of the construction PDS performance is the study by Sanvido and Konchar (1998). This study compared the performance of DBB, DB, and CMGC methodologies of the building construction in the U.S.

On the other hand, there are also investigations of the PDS performance in the horizontal construction industry, but mostly between DBB and DB, such as the studies by FHWA (2006), Shrestha (2007), Shrestha, O'Connor, & Gibson (2012), Minchin, Li, Issa, & Vargas (2013), and Schieber (2014). Thus far only one PDS performance investigation exists regarding CMGC (Shakya, 2013). That study compared CMGC cost performance with DB cost performance. Due to the infancy of CMGC in the horizontal construction industry, the availability of data for Shakya's study was not comprehensive.

This PDS research of the horizontal construction is unique and more comprehensive than previous studies because this research compares three PDS (DBB, DB, and CMGC) all at once, empirically analyzes more sample data (388 DBB, 20 DB, and 38 CMGC), and performs a theoretically sound statistical analysis. A detailed discussion regarding statistical analysis can be found in the Research Methodology section.

Research Objectives

The purposes of this study are (1) to investigate empirically the effect that the three project delivery systems (DBB, DB, and CMGC) have on the Cost Growth and the Change Order Cost Factor in the horizontal construction; and (2) to demonstrate the use of robust analysis of variance (ANOVA) statistical methodology (the bootstrapping M-estimator) to test the hypotheses of mean differences of the unbalanced sample data that also violate classical ANOVA assumptions and to conduct the statistical Planned Contrast analysis to locate where the differences of the means lie, if the ANOVA test indicates statistically significant results.

Motivation and Research Significance

The motivations behind this study are (1) to statistically evaluate the performance of DBB, DB, and CMGC, simultaneously, with respect to the Cost Growth and the Change Order Cost Factor, as such an evaluation has not yet been conducted for the horizontal construction industry; and (2) to find a statistically sound solution for the problem that researchers and practitioners commonly faced when sample data are unbalanced and fail to meet statistical assumptions.

The fact that the U.S. annual construction spending (public and private sectors) in 2015 was $1,112 billion, with transportation/highway and street accounts for $135 billion (U.S. Census Bureau, 2016); these numbers infer that construction industry can involve a large sum of capital investment and profit. Thus, construction managers/owners have been finding ways to better manage their projects. Cost- and schedule-related metrics are frequently used as key performance indicators to measure how well projects are managed and performed. This study focuses on the cost-related aspects.

Thus, the significance of this study is to inform the horizontal construction industry's decision makers of the most effective PDS, among the DBB, DB, and CMGC, by a cost performance comparison. The performance of the three PDS had been compared in 1998 for the vertical construction industry by Sanvido and Konchar (1998); however, it has not yet been compared for the horizontal construction industry.

This study also aims to emphasize the use of the robust ANOVA and the Planned Contrast statistical methodologies in assisting researchers/practitioners when comparing the means of unbalanced sample data that also fail statistical assumptions. There are studies using *t*-tests, when indeed ANOVA is a more appropriate choice, such as the study by Pocock (1996). There are also studies where sample data fail to comply with the normal distribution and/or equality of variance of the ANOVA assumptions, but authors proceeded on with the test with the understanding that the test is robust, such as the study by Shakya (2013). This is the same as in the case of unbalanced data, such as the studies by Pocock (1996), Ibbs et al. (2003), Shrestha (2007), Rojas and Kell (2008), Moon, Cho, Hong, and Hyun (2011), and Shrestha et al. (2012).

Furthermore, this study introduces the use of statistical R-language to help perform the robust statistical analysis. The R-language is considered one of the best statistical software programs (Jureckova & Picek, 2005). It is an open source and provided to the public at no cost (R Core Team, 2013).

Scope and Limitation

This research encompasses horizontal construction projects completed in the State of Utah by the Utah Department of Transportation (UDOT). These projects were constructed using DBB, DB, or CMGC methodologies from January 1, 2008 to July 1, 2015; and with a construction cost of more than $1 million.

On the other hand, the scope of the robust statistics and the Planned Contrast process and application is limited to the following.

- The robust statistical methodology chosen for this study is the bootstrapping M-estimator.
- The two Planned Contrast functions employed in this study are the Helmert contrast and the Treatment contrast.
- The robust ANOVA test and the Planned Contrast analysis are calculated using the R-language statistical program at 95% confidence level.

Literature Review

This section discusses the existing studies relevant to the concepts of the PDS and the performance comparison among the three types of PDS (DBB, DB, and CMGC).

Project Delivery System (PDS)

According to AIA and AGC (2011), PDS involves the delegation of responsibility for providing design and construction services in a project. Similarly, according to Sanvido and Konchar (1998), PDS outlines the sequence of the project activities, and the relationships, roles, and responsibilities of the team members. Rojas and Kell (2008) indicated a project delivery system is differentiated by how the parties contractually and informally relate and how the processes of delivering and project sequencing occur. Thus, based on this information, PDS entails the concept of sequential processes; contract agreement; and parties' relationships, roles, and responsibilities.

The three PDS (DBB, DB, and CMGC) studied in this research are the principle PDS practiced in the U.S. (Sanvido & Konchar, 1998). The DBB is the traditional PDS (Sanvido & Konchar, 1998). The DB and the CMGC are the two preferable alternatives used in place of the DBB (Rojas & Kell, 2008). Rojas and Kell (2008) also indicated that the anticipated paybacks of using the DB and the CMGC are the reduction in claims, litigation, and cost and schedule uncertainty; and the improvement in the stakeholders' relationship and the quality of design and construction.

Design-Bid-Build (DBB). AIA and AGC (2011) and Miller, Garvin, Ibbs, and Mahoney (2000) defined Design-Bid-Build as the traditional PDS where a designer produces construction documents (CDs) for an owner. The owner then uses the CDs for a request for a proposal from contractors. A construction contract will be awarded to the lowest bidder. Thus, the designer and the construction contractor engage in the project sequentially. Because DBB parties are engaged in sequential phases, there is little information sharing or interaction of the design and the construction parties during project phases. This lack of collaboration between project parties, especially during the design phase, has been shown to result in inefficient design and a reduced possibility of constructability (Sanvido & Konchar, 1998).

FMI/CMAA (2010) found that the DBB continues to be the most used project delivery system. However, FMI/CMAA projected that for large projects, the dominance of DBB is likely to be eroding.

Design-Build (DB). Based on AIA and AGC (2011), the DB becomes a well-received alternative PDS due to the owner having a preference for a single contract with a sole party (an integrated team) who is responsible for both design and construction activities. The integrated team develops an innovative design and construction plans, ensures quality and economy along with minimized risk and elimination of contract change orders. Shakya (2013) stated that the benefits of the DB to the owner are: the single point responsibility, low cost, accelerated schedule, and shifting risk to contractors.

Construction Manager/General Contractor (CMGC—also known as CM/GC, GC/CM, CM at-Risk, CM@R, CMAR, and CMR). Under the CMGC delivery system, according to AIA and AGC (2011), the Construction Manager (CM) who provides preconstruction services to the design team during the design phase, takes on the at-risk agreement to become a General Contractor (GC) for the construction phase. They are thought to be able to absorb more risk than the construction contractor/GC of the traditional DBB because of the inside information they gain during the preconstruction services to the design team.

Thus, the key distinction between the CMGC and the traditional DBB is the early engagement of the construction team during the design phase. This early involvement during the preconstruction phase leads to the opportunity to improve product quality and constructability, and to speed up the design and construction schedules. Schierholz (2012) noted that the early involvement during the design phrase is the crucial value added to the process.

Prior Studies of The PDS Performance Comparison

Vertical Construction Studies.

Performance Comparison of Three or More PDS. The most widely cited and accepted research on the performance of alternative delivery methods for construction is the study of Sanvido and Konchar (1998) for the Construction Industry Institute (Carpenter, 2014). It is the cost, schedule, and quality performance comparison study of 351 U.S. vertical construction projects completed from 1990 to 1996, which consisted of 116 DBB, 155 DB, and 80 CMR. The study sample data consisted of a wide range of projects in terms of project size, types, and ownership. The univariate analysis was utilized to compare descriptive statistics. However, the impact of PDS on performance metrics was evaluated utilizing the multivariate linear regression.

The findings of Sanvido and Konchar (1998) concluded that DB outperformed DBB and CMR (separately) and CMR outperformed DBB in the areas of construction and delivery speed, schedule growth, and unit cost. In terms of cost growth, DB outperformed DBB and CMR; however, CMR did not outperform DBB.

Another performance comparison study of DBB, DB, and CMR was performed by Korkmaz, Riley, and Horman (2010). The study included 40 public and private green-office buildings. Of the study projects, there were 14 DBB, 10 DB, and 16 CMR. The study indicated that, in terms of delivery speed, DB and CMR were superior to DBB. On the other hand, the results of the cost growth were inconclusive.

Korkmaz et al. (2010) performed analysis using univariate and multivariate analysis. However, it was noted in their study that the sample size was limited due to the relative infancy of the green-building industry.

In a different comparison of more than three PDS, Pocock (1996) compared four PDS (DBB, DB, Partnered, and Combination) in military construction projects. In his study, the performance of 90 traditional DBB projects was compared to 40 DB, 63 Partnered, and 16 Combination projects. The study concluded that, of 209 projects, the Partnered projects had the least schedule growth and the DB had the lowest cost growth and design deficiencies. The traditional DBB projects had the worst average schedule growth, modifications, and design deficiencies (Pocock, 1996). Note that for this study, Pocock (1996) referred Partnered projects to the projects that practiced a non-contractual agreement, which attempt to promote the achievements of mutually beneficial goals between the owner and the contractor. On the other hand, the Combination projects referred to the projects that utilized the combination of the alternative (DB and Partnered) approaches.

The Pocock (1996) study is significant because of its incorrect use of the statistical *t*-test. The statistical *t*-test should not be used as a statistical methodology for comparing more than two PDS/groups of sample.

Performance Comparison between Two PDS. Ibbs et al. (2003) studied 30 DBB and 24 DB building construction projects in the U.S. and overseas in the areas of cost and schedule growth and productivity. Ibbs et al. (2003) concluded that DB outperformed DBB in terms of schedule growth. On the other hand, the study did not find DB outperformed DBB in the areas of cost growth and productivity. The productivity metric for the study referred to the ratio of earned labor-hours and expected labor-hours.

Hale et al. (2009) conducted the study of the U.S. Navy Bachelor Enlisted Quarters construction projects and concluded that, of 39 DBB and 38 DB, DB was statistically superior to DBB in the performance of cost (cost per bed and cost growth) and schedule (duration per bed and duration/time growth).

Rosner et al. (2009) studied the U.S. Air Force's military construction program and concluded that, of 557 DBB and 278 DB, three of the six metrics (total project time, cost growth, and modifications per $million) were statistically significant. The DB outperformed the traditional DBB in cost growth and modifications per $million. However, for the total project time, the DB did not outperform the DBB. The other three metrics (estimate per budget, unit cost ($\$/m^2$), and schedule growth) were found to be statistically insignificant.

Fernane (2011) analyzed 42 DBB and DB university construction projects each within the U.S., for a total of 10 metrics, in three metrics categories: cost, schedule, and change order cost. The study concluded that DB was significantly superior to DBB in one performance metric under cost category (contract award cost growth), in three performance metrics under schedule category (construction intensity, total and design-plus-construction schedule growth), and in two performance metrics under change order cost (total and construction change order cost growth). The rest of the four metrics (cost per square foot, total and construction cost growth, and design change order cost growth) showed insignificant results.

Williams (2003) compared the performance of DBB and CM/GC of 215 publicly funded projects in Oregon. The 215 projects comprised of 104 DBB and 111 CM/GC. The study concluded that the cost and schedule control performance metrics between DBB and CM/GC were not statistically significantly different.

The study by Septelka and Goldblatt (2005) evaluated GC/CM (CMGC) utilized in the State of Washington. The study revealed that overall the GC/CM (CMGC) outperformed DBB in terms of schedule and cost, and complied with the quality standard 98% of the time. The study included 108 state and local agency projects executed in the State of Washington in the period of 13 years.

Rojas and Kell (2008) evaluated the performance of the construction projects of the Pacific Northwest (Oregon and Washington) public schools. The study analyzed the cost performance metrics of 273 DBB and 24 CMR. Their results indicated the construction change order cost between DBB and CMR was not statistically significantly different. In addition, their results indicated CMR did not statistically outperform DBB in terms of the cost growth. Note that this study used *t*-test to conduct statistical analysis with unbalanced sample data. There were 273 DBB projects compared to only 24 CMR projects.

Carpenter (2014) studied the performance of the construction projects of the Southeast (Florida, Georgia, North Carolina, and South Carolina) public schools. The study analyzed the productivity, quality, cost, schedule, and risk performance metrics of 86 DBB and 57 CM at-Risk. The study found CM at-Risk was statistically significantly superior to DBB for the quality performance metric only. For all other performance metrics (productivity, cost, schedule, and risk), DBB was found statistically insignificantly superior to CM at-Risk.

Maharjan (2013) and Shrestha et al. (2014) studied the owner's satisfaction in the quality of the water and wastewater facilities constructed using DB and CMAR (CMGC). Surveys were sent to 455 owners, but the study did not indicate the response rate. Their results revealed that DB significantly outperformed CMAR (CMGC) in terms of owners' satisfaction in the completed project quality.

Horizontal Construction Studies. For the horizontal construction industry, there has not been a study conducting three or more PDS performance comparison that includes CMGC delivery system. There are several studies comparing performances of DB with DBB in the horizontal construction industry.

FHWA (2006) evaluated the survey results of the DB and DBB in the areas of duration, cost, and quality. The study concluded that DB was able to reduce the total project cost by 3% and the overall duration by 14%; and at the same time maintain the same quality level as the DBB.

Shrestha (2007) conducted the performance comparison study of 11 DBB and 4 DB large highway projects. The performance metric categories of interest were cost, schedule, change orders, safety, and quality. The study concluded that DB outperformed DBB in cost growth, cost per lane mile, and change cost factor. However, DB did not outperform DBB in the schedule growth. The fatality and the quality rating for the DB were similar to that of the DBB. Note that the study used a very small (and unbalanced) sample data to conduct statistical analysis. Shrestha (2007) remarked that "The sample size of this study was small; therefore, it should be noted that this small sample size is not likely to be statistically representative of all large DB and DBB highway projects."

Shrestha et al. (2012) investigated the performance of 16 DBB and 6 DB in the areas of speed, cost, schedule, and change orders. The study revealed DB and DBB were not statistically different in terms of cost and change order related metrics. On the other hand, the study found DB statistically outperformed DBB in delivery and construction speed per lane distance. However, the total schedule growth of the DBB was not significantly greater than schedule growth of the DB. Note that the study by Shrestha et al. (2012) also performed statistical analysis with small and unbalanced sample sizes.

Minchin et al. (2013) studied the performance comparison of 30 each of DBB and DB of the Florida Department of Transportation's projects in the areas of cost and duration. The study concluded that DBB significantly outperformed DB in terms of cost metric; however, the results concluded otherwise for the duration (schedule) performance metric.

Schieber (2014) investigated the DB impact on performance outcomes of bridge construction projects in five categories (17 metrics), including construction cost, construction schedule, change management, quality, and legal implications. The research found that DB showed significantly less construction schedule growth. However, there is no statistical significance in the performance of cost, change order, quality, and legal implications. It should be noted that the analyses were based on a small sample size. There were only eight DBB and only nine DB projects.

Recent research by Shakya (2013) studied the PDS performance comparison of the highway projects (in terms of cost, change order, and construction intensity). The study consisted of 55 DB and 34 CMGC from various states. Shakya's study revealed that DB outperformed CMGC in the construction intensity and the change order cost factor. Moreover, interestingly, the study found conflicting results between two cost performance metrics: the contract award cost growth and the total cost growth. DB was found to significantly outperform CMGC in the contract award cost growth metric; however, this was not true for the total cost growth metric. Shakya believed these cost conflicting findings were the result of the low bid of DB projects in comparison to CMGC projects.

Though Shakya (2013) adjusted project data for location differences, it should be pointed out that all of the DB projects were in the east, but all of the CMGC projects were in the west. In addition, Shakya's study took design phase cost into consideration.

Thus, the cost performance metrics in Shakya's study referred to the design cost plus the construction cost.

Shakya's study did not use the statistical *t*-test, but rather the ANOVA test. Shakya stated "The advantage of using ANOVA was that the number of observations in each group was not necessarily equal." This is not a valid statistical reason to use ANOVA for the study. The ANOVA test should be used only when comparing means of two or more groups.

Summary and Gaps

In the construction industry, DBB is the industry's traditional PDS (Sanvido & Konchar, 1998). DB and CMGC are the two popular alternative PDS (Rojas & Kell, 2008). Studies have been conducted to confirm the industrial belief that the two alternative PDS (DB and CMGC) are indeed superior to the traditional DBB, and also to determine which alternative PDS is better.

There have been many PDS performance comparison studies of the DBB, DB, and CMGC in the vertical construction industry. Most of the studies compared the performance of two PDS, while only a few compared three or more PDS. For those that compared the performance of two PDS, *t*-test was the common methodology employed. The benchmark of the three PDS (DBB, DB, and CMGC) performance comparison was the study conducted by Sanvido and Konchar (1998) for the Construction Industry Institute (CII). The study utilized univariate and multivariate statistical analysis as the methodologies.

In the horizontal construction industry, the DB and CMGC were adopted to the industry later than in the vertical industry. Thus, their infancy contributes to the limited availability of the research data—especially for the CMGC, which was introduced to the industry after the DB. Consequently, there are PDS performance comparison studies in horizontal construction, but mostly DBB is compared with DB. There is a study conducted by Shakya (2013) that compared DB with CMGC. There has not been a performance comparison of the three PDS (DBB, DB, and CMGC) in horizontal construction as Sanvido and Konchar (1998) did in vertical construction. Thus, this study serves to close this gap.

Research Methodology

This section discusses research methodologies that entail performance metric equations and calculations employed to derive the Cost Growth and the Change Order Cost Factor, then continues the discussion regarding the dataset and requirements, and concludes with the statistical process and methodologies.

Performance Metrics

The Construction Industry Institute (CII; n.d) established the Performance Metric Formulas and Definitions that include five metric categories: cost, schedule, safety, changes, and rework.

Based on available sample data and information, this study conducts a performance comparison of the three PDS using two metrics: the construction Cost Growth and the construction Change Order Cost Factor. The construction Cost Growth, which falls under the *Cost Performance Metric* category (CII, n.d.), refers to the escalation of the construction cost compared to the original construction contract amount. In the construction industry, the escalation of the construction cost is contractually documented as the contract change order. Thus, the construction Cost Growth is the proportion of the construction change order amount relative to the original construction contract amount. On the other hand, the construction Change Order Cost Factor, which falls under the *Changes Performance Metric* category (CII, n.d.), refers to the cost estimating relationship in which the change order cost is proportional to the actual construction cost.

The two performance metrics, Cost Growth and Change Order Cost Factor, are both project performance indicators; but they provide different perspectives of project performance. The construction Cost Growth performance metric indicates the escalation (growth) of the construction cost compared to the initial construction cost of the project was planned/budgeted for. On the other hand, the construction Change Order Cost Factor indicates the factor of cost increased due to scope and project development changes for each dollar of the actual construction cost. Due to this reason and the availability of sample project data, the two performance metrics were considered for this study.

The construction Cost Growth and the construction Change Order Cost Factor metrics can be written as (CII, n.d.; Sanvido & Konchar, 1998):

$$\textit{Construction Cost Growth} = \frac{\textit{Construction Change Order Amount}}{\textit{Original Construction Contract Amount}} \tag{1}$$

$$\textit{Construction Change Order Cost Factor} = \frac{\textit{Construction Change Order Amount}}{\textit{Actual Construction Cost}} \tag{2}$$

Note that Change Order Cost Factor is also called Cost of Change Order in Schieber (2014), Shrestha et al. (2012), and Shrestha, Migliaccio, O'Connor, and Gibson (2007), and also called Change Order Cost Growth in Fernane (2011).

Dataset and Requirements

Due to the early stage of CMGC, there is limited availability of CMGC sample data throughout the U.S. Based on the experience and information received during the data gathering, Utah is the only state that has sufficient CMGC project data as required for statistical analysis. It was either impossible or empirically impractical to include CMGC project data from other states for this research. Shakya (2013) also confirmed "UDOT is the only state transportation agency with a large number of CM/GC projects."

Thus, the data for this study was from the Utah Department of Transportation (UDOT). They are the horizontal construction projects completed with DBB, DB, and CMGC methodologies from January 1, 2008 to July 1, 2015 and each has a total construction cost greater than $1 million. A total of 388 DBB, 20 DB, and 38 CMGC projects were used in the statistical analysis of this study.

Statistical Methodologies

This section discusses the statistical methodologies utilized in this study. The test hypotheses and the null hypotheses are generated based on the research questions, which are derived from the research objective.

In a previous section, the Cost Growth and the Change Order Cost Factors were calculated. Next, the two performance metrics of the three PDS will be statistically compared and tested.

Research Questions. To achieve the objective of this study, first, statistical analysis will be conducted to prove whether the means of the three PDS (with respect to the construction Cost Growth and the construction Change Order Cost Factor) are equal. If differences exist, steps will be taken to determine where the differences lie. Thus, to succeed this objective, four empirical questions need to be answered:

1. Is there a statistically significant difference among the means of the three PDS (DBB/DB/CMGC) with respect to the construction Cost Growth?
2. Is there a statistically significant difference among the means of the three PDS (DBB/DB/CMGC) with respect to the construction Change Order Cost Factor?
3. If so, for (1), where do the differences lie?
4. If so, for (2), where do the differences lie?

Research Hypotheses. In order to answer the four empirical questions, test/alternate hypotheses and null hypotheses are formulated to use with the robust ANOVA test and the Planned Contrast analysis separately.

ANOVA—Test Hypotheses and Null Hypotheses.

H_A: There is a statistically significant difference among the three PDS (DBB/DB/CMGC) with respect to the mean of their construction Cost Growth.

H_B: There is a statistically significant difference among the three PDS (DBB/DB/CMGC) with respect to the mean of their construction Change Order Cost Factor.

$H_{0\text{ of }A}$: There is no statistically significant difference among the three PDS (DBB/DB/CMGC) with respect to the mean of their construction Cost Growth.

$H_{0\text{ of }B}$: There is no statistically significant difference among the three PDS (DBB/DB/CMGC) with respect to the mean of their construction Change Order Cost Factor.

The equations for the null hypotheses can be written as:

$$H_{0\text{ of }A}: (\mu_{\text{Cost Growth}})_{\text{DBB}} = (\mu_{\text{Cost Growth}})_{\text{DB}} = (\mu_{\text{Cost Growth}})_{\text{CMGC}}$$

$$H_{0\text{ of }B}: \left(\mu_{\text{Change Order Cost Factor}}\right)_{\text{DBB}} = \left(\mu_{\text{Change Order Cost Factor}}\right)_{\text{DB}} = \left(\mu_{\text{Change Order Cost Factor}}\right)_{\text{CMGC}}$$

The robust ANOVA test utilized in this study is a two tailed (non-directional) test. It was used to test the null hypotheses at a significance level (α) of 0.05.

Planned Contrast—Test Hypotheses and Null Hypotheses. The following equations are the summary of the directional (one-tail) test hypotheses and null hypotheses utilized in the Planned Contrast analysis for this study:

$$H_C: \left(\mu_{\text{Cost Growth or Change Order Cost Factor}}\right)_a > \left(\mu_{\text{Cost Growth or Change Order Cost Factor}}\right)_b$$

$$H_{0\text{ of }C}: \left(\mu_{\text{Cost Growth or Change Order Cost Factor}}\right)_a \text{ £ } \left(\mu_{\text{Cost Growth or Change Order Cost Factor}}\right)_b$$

This set of test hypothesis and null hypothesis is applied to the following list of PDS comparison for both Cost Growth and Change Order Cost Factor:

a. Traditional DBB vs. (b) Innovative PDS ("DB & CMGC")
b. DB vs. (b) DBB
c. DB vs. (b) CMGC
d. MGC vs. (b) DBB

Hypothesis Test Methods. In this study, the performance of the three PDS is compared against each other using a robust ANOVA test to confirm differences in means of the construction Cost Growth and the construction Change Order Cost Factor (separately). If differences exist, the Planned Contrast analysis will be performed to locate where the differences lie among the three PDS.

ANOVA. There are three major ANOVA assumptions relevant to this study: normality, homogeneity of variance, and independence of sample data.

The ANOVA test process can be summarized and is shown in Figure 1. If the sample data comply with all three assumptions (which is not the case for this study), then it is appropriate to use the traditional ANOVA F-test. If the homogeneity of variance assumption is violated (Levene's test p-value is less than 0.05), a commonly used robust ANOVA "Welch's F-test" will be used instead of the traditional Fisher's F-test. Welch's F ANOVA does not assume equal variances (Welch, 1951). It uses a correction, which adjusts the degrees of freedom based on the homogeneity of variance.

In case the normality assumption is violated, the sample data may be corrected to conform with the normal distribution assumption by either collecting more data or by transforming data.

For this study, the sample data violate both the homogeneity of variance and the normality assumption. In addition, collecting large sample sizes of DB and CMGC is not possible since the two PDS are not well-established as the DBB. Moreover, since this study aims to compare arithmetic means of the data, transforming data to other forms can significantly distort the study results (Field, 2013). As Cochran (1947) and Keselman, Wilcox, Othman, Rahman, and Fradette (2002) addressed that the classical Fisher's F-test ANOVA is adversely affected by heterogeneous variance and/or non-normal data, and Wilcox (2005) also noted these conditions (especially when sample sizes are unbalanced, as in this study); therefore, the appropriate methodology for this study is the robust ANOVA. There are several approaches of robust methodologies suggested by Wilcox (2005). The robust ANOVA utilized in this study is the bootstrapping M-estimator. Both the bootstrap and the M-estimator are robust methodologies. The bootstrap methodology can be used alone or in conjunction with another methodology, such as the trimmed means and the M-estimator (Wright, London, & Field, 2011).

Planned Contrast. The one-way ANOVA (traditional or robust) tests a hypothesis of whether there are differences among sample means. The end results will only address whether the differences exist. It does not address where the differences exist among groups. To determine where the differences lie, further analysis must be carried out.

Statistically, there are two common ways to indicate where the differences lie among group means when ANOVA test is significant: post-hoc test and Planned Contrast analysis. The distinction between the two tests is whether or not the group means compared were predicted to be different in advance or merely were decided after looking at the data. For example, in this study, it was predicted in advance that, for instance, the mean of DBB cost growth is greater than the mean of "DB and CMGC" cost growth, and the mean of DB cost growth is greater than the mean of CMGC. Furthermore, the post-hoc test only focuses on pairs of groups, e.g., compare group A with group B, and compare group B with group C; whereas the Planned Contrasts analysis allows for more complex configuration, e.g., compare group D with "A, B, and C" as a whole (Blagov & Peart, 2011). Therefore, the Planned Contrasts analysis specifies the prediction and tests it. For these reasons, this study uses Planned Contrast analysis.

The Planned Contrast analysis is a test to contrast the different groups without inflating the Type-I error rate as the t-test would do when comparing more than two groups. The Planned Contrast functions utilized in this study are the Helmert and the Treatment contrasts. If ANOVA test confirms differences exist in means, the alternative PDS ("DB and

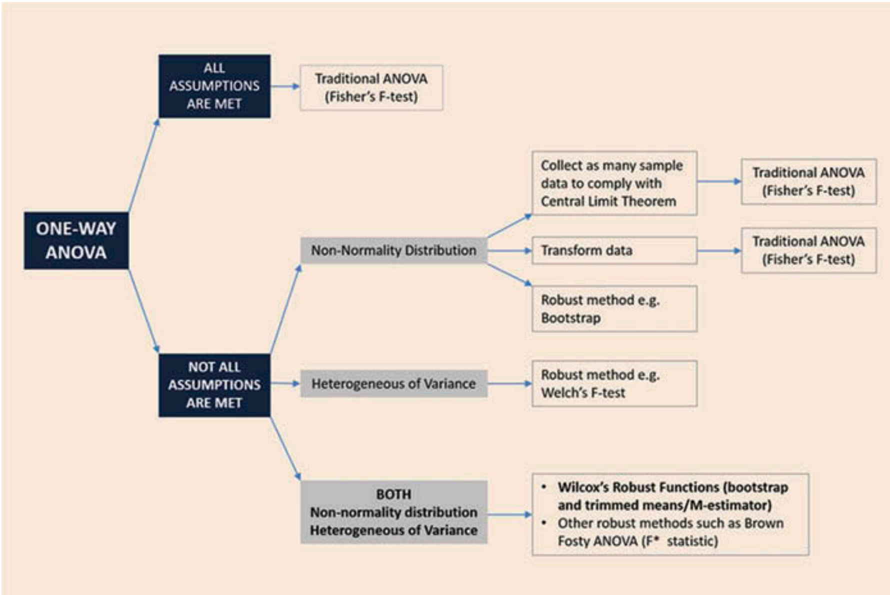

FIGURE 1 ANOVA process.

Descriptive Statistics: DBB-CostGwth, DB-CostGwth, CMGC-CostGwth

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
DBB-CostGwth	388	0	5.428	0.292	5.750	-0.970	0.913	3.670	7.813	24.780
DB-CostGwth	20	0	9.71	1.61	7.18	-4.98	4.11	8.88	14.89	26.09
CMGC-CostGwth	38	0	10.25	1.79	11.03	0.000000000	1.90	5.72	19.94	38.05

Descriptive Statistics: DBB-CostFactor, DB-CostFactor, CMGC-CostFactor

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
DBB-CostFactor	388	0	4.884	0.247	4.867	-0.980	0.910	3.540	7.245	19.860
DB-CostFactor	20	0	8.48	1.33	5.97	-5.24	3.94	8.15	12.95	20.69
CMGC-CostFactor	38	0	8.49	1.35	8.33	0.000000000	1.87	5.41	16.63	27.56

FIGURE 2 Descriptive statistics.

CMGC," as a group) will be compared to the traditional DBB using the Helmert contrast. In addition, each alternative PDS (DB and CMGC, individually) will be compared with the traditional DBB, and will also be compared between themselves (DB and CMGC) using the Treatment contrast.

Research Analysis and Findings

Descriptive statistics of DBB, DB, and CMGC of the construction Cost Growth and the construction Change Order Cost Factor are shown in Figure 2.

Table 1 is the summary of mean, median, and standard deviation of the construction Cost Growth and the construction Change Order Cost Factor of Figure 2. Based on the information shown in Table 1, DBB has the lowest mean and median for both the Cost Growth and the Change Order Cost Factor among the three PDS. DB has the highest median for both the Cost Growth and the Change Order Cost Factor. DB and CMGC are both tied with about the same value of mean for both of the metrics.

TABLE 1 Summary of descriptive statistics

		Construction Cost Growth			Construction Change Order Cost Factor		
PDS	N	Mean	Median	Std. Dev	Mean	Median	Std. Dev
DBB (Design-Bid-Build)	388	5.43	3.67	5.75	4.88	3.54	4.87
DB (Design-Build)	20	9.71	8.88	7.18	8.48	8.15	5.97
CMGC (Const. Mgr/Gen. Contractor)	38	10.25	5.72	11.03	8.49	5.41	8.33

```
> leveneTest(costGrowth.stack$CostGrowth, costGrowth.stack$PDS, center = mean)
Levene's Test for Homogeneity of Variance (center = mean)
       Df F value    Pr(>F)
group   2  23.029 3.055e-10 ***
      443

> leveneTest(costFactor.stack$CostFactor, costFactor.stack$PDS, center = mean)
Levene's Test for Homogeneity of Variance (center = mean)
       Df F value    Pr(>F)
group   2  16.279 1.506e-07 ***
      443
```

FIGURE 3 Levene's Test results of construction cost growth and construction change order cost factor.

ANOVA Assumptions Validation

The boxplots, histograms, and summary of plots were utilized to validate the normality assumption. Levene's test was employed to validate the equality of variance.

The normality assumption validation using the boxplots and the summary plots concluded that the sample data distribution for this study is not normal. This is especially true for the DBB and CMGC sample data, for both the construction Cost Growth and the construction Change Order Cost Factor. (The figures of the boxplots and the summary plots are available upon request to the authors.)

Levene's test results for both the Cost Growth and the Change Order Cost Factor from the R-language are shown in Figure 3. The results show their p-value of less than 0.05. Thus, this information confirms the heterogeneous variance of the Cost Growth and the Change Order Cost Factor of DBB, DB, and CMGC.

Bootstrapping M-Estimator (Robust ANOVA) Results

The results of bootstrapping M-estimator using the R-language statistical program, shown in Figure 4, indicated that the p-value is less than 0.05. Thus, the null hypotheses were rejected at 0.05 level of significance ($\alpha = 0.05$). The results signify that there is enough evidence to support the claim that the means of the DBB, DB, and CMGC construction Cost Growth are different and also that the means of the DBB, DB, and CMGC construction Change Order Cost Factor are different.

Planned Contrast Results

The Helmert contrast was carried out to compare the traditional PDS (DBB) with the alternative PDS ("DB & CMGC," as a group). The Treatment contrast was carried out

```
> b1way(costGrowth.wide, nboot = 2000)
$teststat
[1] 6.481433

$p.value
[1] 0.01

> b1way(costFactor.wide, nboot = 2000)
$teststat
[1] 4.906434

$p.value
[1] 0.004
```

FIGURE 4 Bootstrapping M-estimator results.

to compare each PDS with the base category. For example, DB and CMGC will each contrast with DBB, when DBB is the base category. In the same manner, DBB and CMGC will each contrast with DB, when DB is the base category. DBB and DB will each contrast with CMGC, when CMGC is the base category.

Detailed explanations of the Planned Contrast analysis are in the Appendix. The summary of their statistically significant results are shown in Table 2.

In summary, statistically significant results of the Planned Contrast analysis indicate that the mean of the construction Cost Growth and the construction Change Order Cost Factor of the innovative PDS ("DB & CMGC") is higher than that of the traditional DBB. The DB has a higher average of the two metrics than both CMGC and DBB separately. In addition, between CMGC and DBB, CMGC has a higher average of the two metrics than the DBB.

Summary and Conclusions

This study presents empirical findings of research that compared the performance of horizontal construction projects utilizing DBB, DB, and CMGC project delivery systems. The performance analysis of this study is limited to the construction Cost Growth and the construction Change Order Cost Factor.

The performance comparison of the three PDS (DBB, DB, and CMGC) for the vertical construction was conducted by Sanvido and Konchar in 1998. Their study used surveyed project data in the U.S. completed from 1990 to 1996, which consisted of 116 DBB, 155 DB, and 80 CMAR.

To this day there has not yet been a research study on the performance comparison of the three PDS in the horizontal construction industry that is empirically similar to that of Sanvido and Konchar. For that reason, this is the initial purpose of this study. The derivative purpose of this study is to introduce/re-inform professional peers of the use of the robust ANOVA test and the Planned Contrast analysis for the statistical process in the event that the sample data is unbalanced and violates statistical assumptions (normal distribution and homogeneity of variance). This study also intends to introduce the use of the R-language statistical program. It is one of the best statistical programs, which is also an open source available to the public (Jureckova & Picek, 2005).

TABLE 2 Planned contrast summary results

Cost Growth: Traditional DBB vs. Innovative PDS ("DB & CMGC")
The average Cost Growth of DB is higher than that of CMGC.
The average Cost Growth of DBB (traditional PDS) is less than that of "DB & CMGC" (innovative PDS).
Cost Growth: DBB is the base category
The average Cost Growth of CMGC is higher than that of DBB.
The average Cost Growth of DB is higher than that of DBB.
Cost Growth: DB is the base category
The average Cost Growth of CMGC is less than that of DB.
The average Cost Growth of DBB is less than that of DB.
Cost Growth: CMGC is the base category
The average Cost Growth of DB is higher than that of CMGC.
The average Cost Growth of DBB is less than that of CMGC.
Change Order Cost Factor: Traditional DBB vs. Innovative PDS ("DB &CMGC")
The average Change Order Cost Factor of DB is higher than that of CMGC.
The average Change Order Cost Factor of DBB (traditional PDS) is less than that of "DB & CMGC" (innovative PDS).
Change Order Cost Factor: DBB is the base category
The average Change Order Cost Factor of CMGC is higher than that of DBB.
The average Change Order Cost Factor of DB is higher than that of DBB.
Change Order Cost Factor: DB is the base category
The average Change Order Cost Factor of CMGC is less than that of DB.
The average Change Order Cost Factor of DBB is less than that of DB.
Change Order Cost Factor: CMGC is the base category
The average Change Order Cost Factor of DB is higher than that of CMGC.
The average Change Order Cost Factor of DBB is less than that of CMGC.

The significance of this study is to inform the horizontal construction industry's decision makers of the most effective PDS, among the DBB, DB, and CMGC, by a performance comparison. The selection of a PDS is a crucial aspect to an owner since its process used to manage or oversee design and construction activities has a significant impact to the construction performance (FMI/CMAA, 2010).

The projects utilized in this study was acquired from the Utah Department of Transportation (UDOT). They are the construction projects completed from January 1, 2008 to July 1, 2015 and each has a total construction cost greater than $1 million. The projects are new construction projects and considered each construction phase as an individual project. This study only considered completed projects that have detailed information as required for performance metrics calculations for this study. A total of 388 DBB, 20 DB, and 38 CMGC projects were used in the statistical analysis.

The statistical focus of this research is to evaluate which PDS (DBB/DB/CMGC) performs better in terms of the construction Cost Growth and the construction Change Order Cost Factor. Based on the research questions and the availability and characteristic of the sample data, the statistical methodologies identified for this study are the robust ANOVA test and the Planned Contrast analysis.

In this study, the bootstrapping M-estimator (a robust ANOVA methodology) was chosen to test the null hypotheses of means equality among the performance of the three PDS (DBB, DB, and CMGC). The Planned Contrast analysis was employed to determine where the differences lie when the robust ANOVA's null hypotheses were tested significantly. The Helmert and the Treatment contrasts were the two Planned Contrast functions utilized in this study.

The statistical results of this research concluded that the construction Cost Growth and the construction Change Order Cost Factor provided the same trend of results. That is the alternative PDS ("DB & CMGC" as a group) has a higher Cost Growth and a higher Change Order Cost Factor compared to the traditional PDS (DBB). In addition, the DB has a higher Cost Growth and a higher Change Order Cost Factor compared to DBB and CMGC, separately; and CMGC has higher values for the two performance metrics compared to the DBB.

However, in terms of construction Cost Growth and the construction Change Order Cost Factor, the lower value is better, and the higher value is worse, relative to the project performance. Thus, the findings are interpreted as: traditional PDS (DBB) outperformed the alternative PDS, DBB and CMGC outperformed DB, and DBB outperformed CMGC, for the construction Cost Growth and the construction Change Order Cost Factor.

The findings of the robust ANOVA test and the Planned Contrast analysis align with the results from the descriptive statistics shown in Table 1, particularly the median comparison. That is, the DB has a higher Cost Growth and a higher Change Order Cost Factor compared to the DBB and the CMGC, separately; and CMGC has a higher value for the two performance metrics compared to the DBB.

The reason the findings of the robust ANOVA test and the Planned Contrast analysis align better with the median rather than the mean results from the descriptive statistics is likely due to the fact that the M-estimator is a type of trimming, similar to the trimmed mean, but the commonly used location is the median.

For the performance comparison of the three PDS (DBB, DB, and CMGC), the findings of this study agree with that of Sanvido and Konchar (1998) that, in terms of Cost Growth, CMR (CMGC) did not outperform DBB. On the other hand, this study found that DB did not outperform DBB and CMGC, separately. However, Sanvido and Konchar (1998) concluded otherwise.

In addition, the results of this study agree with some of the previous PDS researches conducting the performance comparison of two PDS. In summary, for both vertical and horizontal construction, in terms of the Cost Growth, the results of this study agree with Ibb et al. (2003) and Minchin et al. (2013) that DB is not superior to DBB; and agree with Rojas and Kell (2008) and Carpenter (2014) that CMR or CM at-Risk did not produce a purported cost benefit over (or is less efficient than) the DBB. However, this study shows conflicting results with Hale et al. (2009), Rosener et al. (2009), Fernane (2011), FHWA (2006), and Shrestha (2007). Their findings agreed with Sanvido and Konchar (1998) that DB was superior to DBB in Cost Growth metric. This study also disagrees with Septelka and Goldblatt (2005) and Shakya (2013). Septelka and Goldblatt (2005) found CM/GC (or GC/CM) outperformed DBB, and Shakya (2013) found DB outperformed CMGC.

In terms of the Change Order Cost Factor, the results of this study do not agree with Fernane (2011), Shrestha (2007), and Shakya (2013). Shrestha (2007) and Fernane (2011) found the Change Order Cost Factor (also called Cost of Change Order and Change Order Cost Growth) of the DB outperforms that of DBB. Additionally, Shakya (2013) found DB to be superior to CMGC for the Change Order Cost Factor.

Closing Remarks and Lessons Learned

Choosing the right PDS for a project is crucial to construction managers/owners since its process used to manage or oversee design and construction activities has significant impact on the construction performance (FMI/CMAA, 2010). The implication that can be drawn from the results of this study is that the alternative PDS is not always superior to the traditional PDS (DBB). In addition, between the two alternative PDS, CMGC is superior to DB. Based on this information, the decision makers/owners should be able to make an informed decision, in regard to cost related aspects when choosing PDS for their project. However, when choosing the most appropriate PDS for a project, managers/owners should also take into consideration of other significant factors; e.g., schedule performance and qualitative aspects, such as skill/experience of the team members.

The work and evidence provided by this study serve to initiate the study of PDS performance of the horizontal construction industry at a wider level (geographical areas and performance metrics).

The difficulty during the data collection process of this study is due to the lack of an existing cohesive and consistent database in the public sector. It was time consuming to conclude that it would not be possible nor technically practical to include project data from states other than Utah, due to the unavailability and the impossibility of obtaining such data.

Common mistakes from other studies discovered during the course of the literature review were the inappropriate use of statistical methodologies when using unbalanced sample data and when performing statistical analysis, for example, using an ANOVA test instead of a *t*-test for two samples (Shakya, 2013), and using a *t*-test instead of an ANOVA test for three or more samples (Pocock, 1996).

Future Research Opportunities

Several possible avenues for future studies in the areas related to comparing PDS in the horizontal construction industry include:

1. Using sample data (DBB, DB, and CMGC) from states across the U.S. This way the findings will infer broader conclusions to the entire U.S.
2. Comparing one geographical area relative to another geographical area. This will be similar to studies completed in vertical construction. For example, Rojas and Kell (2008) conducted DBB and CMR performance comparison of the construction of public schools in the Northwest states; whereas Carpenter (2014) did the same study for the Southeast states.
3. Using performance metrics not covered in this study, such as those listed on CII (n.d.); and qualitative aspects (e.g., technical performance, product quality, and customer satisfaction).
4. Comparing more than three PDS. For example, the state of California might consider comparing the performance of their four PDS: Design-Bid-Build, Design-Build, Design-Sequencing, and Construction Manager/General Contractor.
5. Using other statistical methodologies in place of the bootstrapping M-estimator.
6. Closing the gap in the unbalanced sample data among DBB/DB/CMGC prior to conducting statistical analysis.
7. Using primary sources of data (i.e., survey data, as Sanvido and Konchar [1998] did for their study).
8. Sanvido and Konchar (1998) addressed in their vertical construction study that it would be important to see whether project delivery systems and behavior change

in the subsequent 10 to 20 years. This study suggests the same for the horizontal construction study.

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