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QUANTITATIVE ANALYSIS OF THE IMPACT OF CRAFT LABOR AVAILABILITY ON CONSTRUCTION PROJECT PERFORMANCE

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QUANTITATIVE ANALYSIS OF THE IMPACT OF CRAFT LABOR

AVAILABILITY ON CONSTRUCTION PROJECT PERFORMANCE

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DISSERTATION

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A dissertation submitted in partial fulfillment of the

requirements for the degree of Doctor of Philosophy in the

College of Engineering

at the University of Kentucky

By

Hossein Karimi

Lexington, Kentucky

Director: Dr. Timothy R. B. Taylor, Professor of Civil Engineering

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ABSTRACT OF DISSERTATION

QUANTITATIVE ANALYSIS OF THE IMPACT OF CRAFT LABOR

AVAILABILITY ON CONSTRUCTION PROJECT PERFORMANCE

A shortage of skilled craft labor in the North American construction industry has been an unfortunate cyclic trend since the late 1980s. This shortage has been reported and discussed frequently by numerous past studies in the context of construction industry. The 2008 U.S. recession was at least one period when the craft shortage temporarily improved, as witnessed by spikes in construction unemployment rates above 20% due to the work slowdowns. However, the current economic recovery period is once again experiencing craft shortages in some sectors of the U.S. construction industry. Although the past literature provides wealth of information about influence of craft labor shortage on construction project, less attention has been given to quantifying the impact of craft labor availability on construction project performance. The primary contribution of this study to the body of knowledge is to fill the gap in existing literature by quantitatively modelling and elucidating the influence of craft labor availability on construction project performance as measured by safety, schedule, productivity and cost. Data from 97 construction projects completed in the U.S. and Canada between 2001 and 2014 were collected from two data sources. A number of t-tests and regression analyses were conducted in both databases to examine the significance of the influence of craft labor shortage on construction project performance. The primary analysis shows that projects that experienced craft shortages underwent significant higher growth in cost overrun, time overrun, safety incident and also lower productivity compared to projects that did not. Further analysis on two databases returned the following models: 1) a Poisson regression model that demonstrates a positive exponential relationship between increased craft worker recruiting difficulty and Occupational Safety and Health Administration (OSHA) Total Number of Recordable Incident Cases per 200,000 Actual Direct Work Hours (TRIR) on construction projects. 2) a statistically significant correlation between increased craft recruiting difficulty and lower project productivity and higher schedule overruns 3) a multiple regression models that demonstrate a relationship between increased construction cost overrun with two variables

of increased actual cost and increased craft staffing difficulty. These models are intended to be used by project management team to perceive the risk that skilled craft labor variability poses on project safety, productivity, time, and cost performance. In addition, understanding the level of impact that craft shortages are having through robust statistical analyses is a first step in developing the motivation for industry leaders, communities, and construction stakeholders to address this challenge.

KEYWORDS: Labor Shortage, Safety, Cost, Time, Productivity, Risk Assessment

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Student's Signature

<div align="right">06/28/2017</div>

Date

QUANTITATIVE ANALYSIS OF THE IMPACT OF CRAFT LABOR

AVAILABILITY ON CONSTRUCTION PROJECT PERFORMANCE

By

Hossein Karimi

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06/28/2017

Date

To my parents, parents-in-law

My wife, Adeleh and my children Elina Zahra and Amir Neekan

ACKNOWLEDGEMENT

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CHAPTER 1: INTRODUCTION

1.1. Background and Motivation

A shortage of craft labor in the North American construction industry has been an unfortunate cyclic trend since the late 1980s. In 1983, the Business Roundtable forecasted that a shortage of skilled craft workers would hamper the growth of construction industry by the late 1980s (BRT, 1983). In 1990, the Construction Industry Institute (CII) reported that a shortage of skilled labor already existed in some regions of the U.S. (CII, 1990). CII forecasted that this shortage would worsen through the 1990s partially due to demographic shifts. In 1997, the Business Roundtable confirmed the shortage by reporting that 60% of its surveyed U.S. construction companies experienced difficulties in recruiting and retaining their craft workforce (BRT, 1997). Later, a survey in the U.S. found that 78% of facility owners expressed that the skilled labor shortage had increased during the past years (Rosenbaum, 2001). In 2007, 86% of the leading U.S. construction firms reported they were experiencing craft shortage on their recent performed projects (Sawyer and Rubin, 2007).

The 2008 U.S. recession was at least one period when the craft shortage temporarily improved, as witnessed by spikes in construction unemployment rates above 20% due to the work slowdowns (Construction Industry Institute, 2015). However, the current economic recovery period is once again experiencing craft shortages in some sectors of the U.S. construction industry. The U.S. Bureau of Labor Statistics (2013) predicted that the construction industry would be the fastest growing industry among goods-producing sectors and third among all major industry sectors, with an annual growth rate of 2.6% and

new job openings exceeding 1.6 million over the 2012-2022 period. Taylor et al. (2016) reported that the rapid economic recovery has already caused severe craft shortages in the U.S. Southeast and Southwest regions for specific craft skilled trades, including welders, pipe fitters, and electricians.

Craft labor shortages on a project are initiated by both the available quantity and/or qualification of craft labors. When project managers cannot hire the required quality levels of craft labor, the project is executed with less skilled workers, even if recruiting quantity needs are met. When craft labor quantity issues arise, a project cannot meet its basic labor demands.

Construction is a labor-intensive industry and labor costs comprise a significant portion (30-50%) of the total actual cost of construction projects (McTague and Jergeas, 2002; Hanna et al., 2001). Therefore, the management of labor and productivity is a critical factor in the success of a construction project (Hanna et al., 2005; Ernzen and Schexnayder, 2000). On the other hand, the permeation of skilled labor shortages throughout the North American construction industry over the past decades has made the recruiting and retaining of skilled labors a major challenge, which can adversely affect construction project performance.

1.2. Research Objectives and contribution

It is well known that project cost, schedule, quality, and safety are the four primary measures of construction project performance. Previous research on workforce issues has lacked any large-scale focused on quantifying the impact of craft labor availability on project performance. ***The contribution of this work to the body of knowledge is to quantify***

the influence of skilled craft labor availability on construction project performance as measured by safety, cost, schedule, and productivity performance.

To achieve this purpose, the following objectives were defined: 1) To identify whether there is a significant difference in performance parameters of projects that reported a craft worker shortage versus those that did not; 2) To determine whether there is significant relationship between craft worker recruiting difficulty and performance parameters in projects; and 3) To develop models that quantifiably links project craft worker variability to project performance parameters.

1.3. Dissertation Organization

Scholarly objectives will be accomplished through the development of three papers which will make the following contributions:

- Paper 1: This paper presents an intensive literature review on the impact of craft labor availability on construction project safety performance. Then, it attempts to find whether there is a significant difference between safety performance of project that experienced craft shortage and those did not. For the purposes of this study, safety performance is parameterized by the Occupational Safety and Health Administration (OSHA) Total Recordable Incident Cases per 200,000 Actual Direct Work Hours in the project (TRIR). Further analysis focuses on the relationship between craft staffing difficulty and TRIR. *The contribution of this paper to the body of knowledge is the quantification of the influence of craft worker availability on construction project safety performance.*

- Paper 2: This paper provides an intensive literature review on the influence of skilled labor availability on construction project schedule and productivity performance. The main purpose of analysis on available data is to quantitatively examine the influence of skilled labor availability on construction project schedule performance as measured by actual project time overrun. To elucidate this causal relationship, the relationship between craft labor availability and productivity and the percentage of the overtime usage are examined. ***The contribution of this paper to the body of knowledge is to quantitatively modelling and elucidating the influence of craft labor availability on construction project productivity and schedule performance.***

- Paper 3: This paper examines the influence of craft labor availability on cost performance of construction project as measured by actual project cost overrun. The body of literature is reviewed to find the various influential relationship between craft labor shortage and cost performance. The paper's literature review is built of the foundation of two previous papers and attempts to identify different mechanisms of the impact of skilled labor variability on project cost performance. The analysis on available data is performed to quantitatively modelling the impact of craft labor availability on construction projects cost overrun. ***The contribution of this paper to the body of knowledge is to quantitatively modelling the impact of craft labor availability on construction project cost performance.***

CHAPTER 2: Quantitative Analysis of the Impact of Craft Worker Availability on Construction Project Safety Performance (Paper No.1)

Synopsis: The North American construction industry has experienced periods of craft shortages for decades. While this problem has received significant attention from researchers, less attention has been given to quantifying the impact of craft labor availability on project performance. The primary contribution of the current work to the body of knowledge is the quantification of the relationship between craft labor availability and project safety performance, as measured by Occupational Safety and Health Administration (OSHA) Total Number of Recordable Incident Cases per 200,000 Actual Direct Work Hours (TRIR). A database of 50 North American construction projects completed between 2001 and 2014 was compiled by taking information from a research project survey and the Construction Industry Institute (CII) Benchmarking and Metrics Database. The primary analysis shows that the TRIR distribution of a group of projects that reported craft worker recruiting difficulty tended to be higher than the TRIR distribution of a group of projects with no craft worker recruiting difficulty. Moreover, the average TRIR of the projects that reported craft worker recruiting difficulty was more than two times the average TRIR of projects that experienced no craft recruiting difficulty. Furthermore, the Poisson Regression Analysis demonstrated that there is a positive exponential relationship between craft worker recruiting difficulty and TRIR in construction projects. The Poisson Regression Model is the first model that quantifiably links project craft worker availability to construction project safety performance. There have been significant long-term gains in construction safety within the United States. If recent craft shortages continue, the quantitative analyses presented herein indicate a strong

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possibility that more safety incidents will occur unless the shortages are reversed or innovative construction means and methods should be developed and adopted to work in a safe manner with a less qualified workforce.

2.1. Introduction and Background

A shortage of skilled craft workers in the North American construction industry has been an unfortunate repetitive cyclic trend since the late 1980s. In 1983, the Business Roundtable forecasted that a shortage of skilled craft workers would hinder the growth of the construction industry by the late 1980s (BRT, 1983). In the early 1990s, the Construction Industry Institute (1990) reported that a shortage of skilled trades already existed in some U.S. regions. CII even predicted that this shortage would worsen through the 1990s, partially due to demographic shifts. This prediction was confirmed in 2001 by a survey conducted by the Construction Users Roundtable in which 82% of the respondents reported shortage in their projects (CURT, 2001). In 2007, 86% of the 300 leading U.S. construction firms reported they were experiencing craft shortages on their current projects (Sawyer and Rubin, 2007). The Great Recession of 2008 temporarily relieved the craft shortage due to sharp declines in construction volume, with construction unemployment peaking at more than 20% (Taylor et al., 2016). However, the craft shortage is again emerging within the U.S. construction industry because of recent economic recovery.

The Bureau of Labor Statistics (2013) predicted that the construction industry will be the fastest growing industry among goods-producing sectors and the third among all the major industry sectors, with an annual growth rate of 2.6% and new job openings exceeding 1.6

million over the 2012-2022 time period. Albattah *et al.* (2015) reported that the U.S. construction craft worker pool is losing workers at a faster rate than they are entering the workforce, in part due to the aging workforce. Taylor *et al.* (2016) found that a craft shortage already exists in the U.S. Southeast and Gulf Coast regions for specific craft trades (e.g. welders, pipe fitters, and electricians).

Craft worker problems on a project can be caused by both labor quality and labor quantity issues. When project managers cannot hire the required quality levels of craft workers, the project is executed by less experienced workers even if recruiting quantity needs are met. When craft worker quantity issue arises, a project cannot even meet its labor demands. The impact of craft worker quantity and quality issues on project cost and schedule performance is a well-understood and studied problem within construction academia (Abdul-Rahmaan *et al.*, 2006; Kaming *et al.*, 1997; Toor and Ogunlana, 2008; Elinwa and Joshua, 2001; Jergeas and Ruwanpura, 2010; Arditi *et al.*, 1985). Less understood is the impact of craft worker shortage on project safety performance.

2.2. Craft Shortage Impact on Project Safety Performance

Projects encountering craft worker shortages usually experience tight scheduling in order to meet the project deadline. Three traditional options for accelerating the work are overtime, shift work, and overmanning (Hanna et al., 2005). Overtime scheduling is the only possible option for these projects. Overtime duties can cause physical fatigue on craft workers (Lyneis and Ford, 2007), which can seriously affect implementation of construction site safety (Cheng et al., 2004). Ahmed et al. (1999) identified a tight construction schedule as the most serious factor affecting construction site safety. Another

impact of tight scheduling is the higher work pressure on craft workers. The evidences of the influence of perceived work pressure by workers on unsafe work behavior have been discussed by several researchers. They claimed that workers tend to take safety shortcuts when they feel they are under pressure during the work (Choudhry and Fang, 2008; Brown et al., 2000).

Less experienced workers are more prone to safety incidents due to the lack of familiarity with proper construction procedures and processes. Choudhry and Fang (2008) found that experience has a significant role in unsafe behavior of craft workers. Glazner et al. (2005) found that factors such as inappropriate acts, inexperience, and deviations from safety instructions were the most common reasons for injuries, contributing to 54.4% of all observed injuries in their study. There are several studies that cite human error as one of the major risk factors of construction safety incidents. Chi et al. (2013) analyzed 9,358 safety incidents and found that judgments or perceptions of craft workers have significant impacts on safety incidents. They also found that 19% of the total of 326 fatal caught-in or -between accidents and 6% of the total of 2,409 struck-by or -against accidents could have been addressed by controlling craft workers' judgment or perception toward required working action. Hinze et al. (2005) analyzed 743 struck-by accidents and found the misjudgment of a hazardous situation is the most common human factor contributing to accidents, accounting for 35.8% of the total observed cases in the study.

While this study attempts to find the influence of craft worker shortage on the safety performance parameter of Incident Rate, it is worth mentioning that the impact of craft worker shortage on project safety climate, as one of the safety leading indicators in a construction site environment, remains a substantial factor. Mohamed (2002) found a direct

relationship between competence level of workers and safety climate. The Competence Construct in the presented model is defined by the capability craft workers have in identifying potentially hazardous situations, the level of job safety training, and the familiarity with relevant safety procedures and legislations. Mohamed also identified an indirect negative influence of work pressure on the safety climate. This happened when pressured workers took time-saving shortcuts. The impact of craft worker availability on the two constructs of the safety climate model demonstrated the essential role of craft worker availability on construction project safety performance.

Over the past two decades, there have been significant long-term gains in construction safety within the U.S. For example, the fatality rate in construction declined from 14.24 to 9.4 per 100,000 full-time equivalent workers from 1992 to 2010, which accounted for a 34% drop (CPWR, 2013). However, if the qualified craft worker shortage in the construction industry continues or worsens, can construction projects suffer from its impact on safety performance? This study attempts to identify the impact of skilled craft worker shortage on safety performance of construction projects. To achieve this purpose, the following three objectives were defined: 1) Identify whether there is a significant difference in safety performance of projects that reported a craft worker shortage versus those that did not; 2) Determine whether there is significant relationship between craft worker recruiting difficulty and safety performance in projects; and 3) Develop a model that quantifiably links project craft worker availability to safety performance. For the purposes of this study, safety performance is parameterized by the Occupational Safety and Health Administration (OSHA) Total Recordable Incident Cases per 200,000 Actual Direct

Work Hours in the project (TRIR). TRIR is a standard measure of safety performance in the North American Construction Industry.

2.3. Research Methodology

2.3.1. Data Collection

The data used in this study were obtained from two different sources. The first source was a primary data collection through the Construction Industry Institute (CII) Research Team Number 318 (RT-318) survey. The RT-318 survey tool was developed by RT-318 in order to collect demographic data on completed construction projects performed in the U.S. and Canada. The total responses to the survey were 29 projects; 26 projects were from the U.S. and three were from Canada. Most of the survey responses involved Heavy Industrial projects (19 out of 29), while the remaining projects were Building, Light industrial, or Infrastructure. All projects were performed between 2010 and 2014. The results of this survey were used to construct a database of project characteristics (e.g. cost and time performance, craft shortages level, and TRIR). Additional detail on this survey data collection is described in Taylor et al. (2016).

The second source was the existing CII Benchmarking and Metrics (BM&M) database of completed projects. The CII BM&M is a database maintained by CII which is designed to capture the comprehensive data of construction projects performed in the U.S. and Canada. For the purpose of this study, the projects in this database that reported those data pertinent to the analysis were selected. The dataset consisted of 68 completed projects, of which 59 were performed in the U.S. and 9 in Canada. Thirty-one of the projects (45%) were Heavy

Industry projects, 24 projects (35%) were Commercial Building, and the others were Light Industrial or Infrastructure projects (20%). All the projects in the CII BM&M database were completed between 2001 and 2013.

2.3.2. Database Construction

To increase the fidelity of the data, the two data sources were combined into a single database. Romeu (2004) argues that combining datasets should only be done when there is no large statistical difference between associated distributions and their parameters. There also should not be significant difference between regression models of two databases if regression analysis is to be performed on the combined dataset. Therefore, before combining the two datasets, the authors compared the Actual Project Cost, Actual Project Time, and TRIR of the two databases. The Mann-Whitney Test was chosen to test the significant difference between the distributions of each variable in the two databases. The null hypothesis in this test asserts that two variables have the same probability distribution, however, the common distribution is not specified. The alternative hypothesis specifies that the distribution of one variable tends to be larger (or smaller) than another variable. The advantage of this test is that it does not require the assumption of normality as it is classified as a distribution-free rank sum test. It compares median rather than mean and hence, if the data have one or two outliers, their influence would be neglected. The three assumptions of this test are that the two datasets have the same probability distribution, that they be random and independent from each other, and that the data are quantitative continuous variables (Hollander et al., 2014). In the two datasets, all the assumptions are satisfied for variables except for the Actual Time variable. The distribution of the Actual Time variable in the RT-318 survey projects is close to the normal distribution but it is

positively skewed in the CII BM&M. Hence, the test cannot be performed to compare the Actual Time variable from two databases. Nevertheless, the median of this variable in both datasets is close —678 compared to 533—which indicates no substantial difference between two distributions. The total number of projects with available data points of Actual Cost and TRIR was 95 and 50, respectively. The significance level (α) for the test was 0.05. The P-value of the test for Actual Cost and TRIR was 0.367 and 0.566 respectively, which indicated that there was no significant difference between distributions of these two variables between the two databases. The result of the test is shown in Table 1.

Table 2.1. Mann-Whitney Test for comparing TRIR and Actual Cost of BM&M and RT-318 Survey Projects

Variable	Actual Cost			TRIR		
	N	Mean Rank	Sum of Ranks	N	Mean Rank	Sum of Ranks
CII BM&M	68	46.38	3154	37	24.86	920
RT-318 Survey	27	52.07	1406	13	27.31	355
Total	95	–	–	50	–	–
Mann-Whitney U	808			217		
Z	-0.908			-0.595		
Exact Sig. (2-tailed)	0.367			0.566		

Since the regression analysis will be performed on the combined databases, the authors examined the difference between the two regression models from the two databases and found no significant difference between them. This will be discussed later in the regression analysis section. Finally, after ensuring there were no substantial differences between the

two databases and associated regression models and also after checking for possible project duplication between them, the databases were merged into a single database. Table 2 shows summary information for the two databases and for the combined database used to conduct this research.

Table 2.2. Actual Cost and Actual Time of RT-318 Survey, BM&M, and Combined Database

Database	Cost ($M) Schedule(Day)	Average (Median)	Min, Max
RT-318 Survey	Cost	455.15 (45)	3.6, 8549
	Schedule	554.65 (533)	134, 1648
CII BM&M	Cost	142.49, (40.1)	0.5, 1799.3
	Schedule	1054.48, (678)	46, 3131
Combined Database	Cost	231.3 (40.8)	0.5, 8549
	Schedule	913.2 (622.5)	46, 3131

2.3.3. Craft Worker Availability Measurement

RT-318 Survey Tool

To quantify the impact of craft worker availability on project safety performance, an estimate of the level of the shortage experienced in the projects was needed. In the RT-318 survey, the respondents were asked to indicate the level of craft recruiting difficulty they experienced in their project across the 13 craft worker trades: Carpenter, Pipefitter, Electrician, Boilermaker, Sheet metal worker, Ironworker, Pipe welder, Structural welder, Equipment Operator, Crane Operator, Millwright, Instrument fitter, and Supervisor. There were five levels of recruiting difficulty defined in the survey ranging from No Difficulty to Very Severe. Table 3 shows these levels, their scores, and also their definition provided in the RT-318 survey.

Table 2.3. Levels of impact of craft worker recruiting difficulties in RT-318 Survey projects

Level	Definition	Score
No difficulty	There was no shortage. Able to staff the project with no delay on construction	0
Slight	Staffing difficulties led to consumption of schedule float and/or contingency	1
Moderate	Staffing difficulties led to delay of completing project activities on time	2
Severe	Staffing difficulties led to delay of completing project milestones	3
Very Severe	Staffing difficulties led to project delay	4

To provide an overall picture of craft recruiting difficulty across a variety of projects and trades, the authors aggregated the data by calculating an average score of recruiting difficulty of these 13 trades for each project as:

$$\text{Project Craft Recruiting Difficulty Score} = \frac{(0 \times A) + (1 \times B) + (2 \times C) + (3 \times D) + (4 \times E)}{13}$$

in which A, B, C, D, and E are the total number of trades in each level of recruiting difficulty from No difficulty to Very Severe.

CII BM&M Database

In the CII BM&M database, the respondents indicated the availability of skilled workers with regard to what was specified in the planning stage of their projects. This level ranges from Extremely Negative (-5) to Extremely Positive (+5), and Zero indicates an "As Planned" situation.

2.3.4. Converting and merging measurement scales across the databases

Since the two databases had different scales to measure craft worker availability, it was necessary to merge the scales into a single measurement. To accomplish this, the CII BM&M scale was converted to the RT-318 scale. Any number between zero (As Planned) to +5 (Extremely Positive) was converted to No difficulty level (0) as defined in the RT-318 survey. This conversion was based on the assumption that projects with scores in this range were not impacted by a shortage of craft workers. The BM&M questionnaire defined zero scores as the situation of the original plan and defined scores greater than zero as the condition that the availability of craft workers had a positive impact on project performance. Therefore, it can be reasonably assumed that when the BM&M score is equal to or greater than zero, a project experienced no craft worker recruiting difficulty. There were only six projects among a total of 50 projects used for analysis that had scores of more than zero. The scores between -5 (Extremely Negative) to -1 in the CII BM&M were also scaled proportionally to the number between 1 (Slight) to 4 (Very Severe), as defined in the RT-318 survey. This can be done by multiplying any score between -1 and -5 by -4/5. Fig. 1 illustrates the whole scale conversion process.
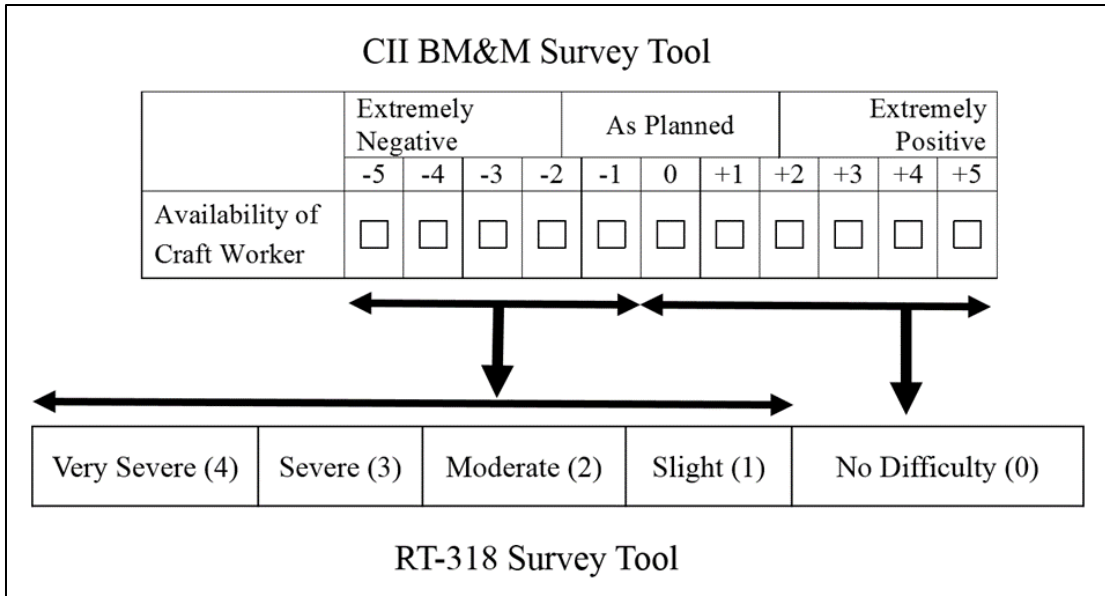
Figure 2.1. Process of converting the BM&M scale of availability of craft workers to RT-318 survey scale

2.4. Data Analysis

2.4.1. Hypothesis Development

After conversion of the craft worker availability score from the CII BM&M into the RT-318 survey scale, the projects were divided into two groups: 1) those with no recruiting difficulty (Score = 0), and 2) those with recruiting difficulty (Score > 0). To determine the significance of the impact of craft labor shortage on project safety performance, the following hypothesis was developed: The TRIR in projects that experienced craft labor shortage is higher compared to projects not experiencing craft labor shortage. The hypotheses is provided in detail in Table 4.

Table 2.4. Summary of Hypothesis Development

Projects Classification	Null Hypothesis	Alternative Hypothesis
projects with no craft recruiting difficulty (1) vs. projects with craft recruiting difficulty (2)	There is no difference in TRIR between group 1 and 2	The TRIR is higher in group 2

First, the Mann-Whitney Test compared the whole distribution of TRIR in two groups. The P-value of the test was 0.004 which resulted in rejection of the null hypothesis and a conclusion that the TRIR distribution in groups of projects that experienced craft worker recruiting difficulty tends to be higher compared to the group of projects with no craft worker recruiting difficulty. The result of the test is shown in Table 5. In addition, the T-Test was performed to check whether there is significant difference between averages of TRIR between these two groups. As shown in Table 6, the average of TRIR among the group of projects with no craft worker recruiting difficulty was 0.3 compared to the 0.68 which was the average TRIR for the projects that reported craft recruiting difficulty. The P-value of the test was less than 0.05 which again led to rejection of null hypothesis. The result of the test is shown in Table 6.

Table 2.5. Comparison of the TRIR distribution between projects with & without craft worker recruiting difficulty

Projects	N	Mean Rank	Sum of Ranks
Recruiting Difficulties = 0	27	21.07	569
Recruiting Difficulties > 0	23	30.70	706
Total	50	–	–
Mann-Whitney U			191.0
Z			-2.665
Exact Sig. (1-tailed)			0.004

Table 2.6. Comparison of the TRIR mean between projects with & without craft worker recruiting difficulty

Project Safety Performance	Recruiting Difficulties = 0			Recruiting Difficulties > 0			T	Df	P
	Mean	SD	N	Mean	SD	N			
TRIR	0.30	0.64	27	0.68	0.776	23	1.85	48	0.035

2.4.2. Poisson Regression Analysis

The Poisson probability model, which is in the exponential dispersion family, is often used for simulation of the variables that refers to the number of times an event occurs randomly over time or at particular rate (Agresti, 2015). Two examples of this type of variable are the number of car accidents that happen in a city per day, or the number of insurance claims within a given period of time. There have been a number of scholars that applied the Poisson regression model to simulating construction incident occurrence. Chua and Goh (2005) argued that Poisson distribution is a suitable model for modelling construction incident occurrence. They showed that incident records of all except one of their 14 studied major construction projects were modelled by a homogenous Poisson process. They argued that there was no evidence to reject the Poisson distribution for modelling construction incident occurrence. Glazner *et al*. (1999) used Poisson regression analysis to examine the association between contract injury rates and contract safety practices. They found that two contract practices of "disciplinary action always resulting when safety rules were violated" and "always considering experience modification rating when selecting subcontractor" were associated with a lower injury rate in construction projects. Bailer *et al*. (1997) used Poisson regression analysis to model fatal injury rates of workers in Agriculture, Forestry,

and Fishing. They found that men experienced a weak but statistically significant decrease in injury rate from 1983 to 1992 in these industries, while women experienced a strong and statistically significant increase in injury rate over the same period of time.

The dependent variable used in the regression analysis was the TRIR, which is the OSHA Total Number of Recordable Incident Cases per 200,000 Actual Direct Work Hours in a project. Chua and Goh (2005) argued that when using a Poisson distribution, the occurrence of an event need not be measured in the time unit, and it can be counted in any continuum such as space or person-hour working time. The Poisson distribution is a derivation of a binominal distribution where the number of trails increases and the probability of success decreases accordingly (Tutz, 2012). For these small intervals, success can be defined as one occurrence of a desired event. Since it is a reasonable assumption in construction projects that person-hour parameters be partitioned into n small equal subintervals in which one accident at most can happen (Chua and Goh, 2005), the Poisson distribution can be used for modelling TRIR. Another assumption of the Poisson distribution is that the observations should be independent from each other (Agresti, 2015). Since the TRIR on a construction project does not reasonably influence the TRIR on other projects, this assumption was also satisfied. Moreover, in the Poisson distributions, there is no upper limit on the values that may be observed (McCullagh and Nelder, 1983). This situation is similar to the actual situation of accidents' occurrence among construction projects. The mass function of probability in this model is defined as:

$$P(y, \mu) = \frac{e^{-\mu} \mu^{y}}{y!} \qquad \text{for } y = 0, 1, 2, ...$$

in which the mean (μ), variance, and all other cumulants of Y are equal (McCullagh and Nelder, 1983). The Poisson regression model is the standard model for count data in which

n independent observations (y_i, x_i) are assumed to be Poisson-distributed with mean μ_i (Tutz, 2012). It also should be noted that the safety data points in this study were Poisson-distributed, which justifies the application of the Poisson regression model for simulating the relationship between craft recruiting difficulty and TRIR.

2.4.3. Poisson Log-linear Regression Model

The log-linear model of Poisson distribution is the most common model which uses a log link to connect the mean to the linear predictor variable (Agresti, 2015). The equation of the model is:

$$\text{Log } (\mu) = x'\beta$$

in which μ is the mean and x' is the predictor variable. The independent variable of the regression model was the Recruiting Difficulty Score and the response variable was the TRIR from the combined RT-318 and CII BM&M database. The total number of available data points for this analysis was 50 projects. Table 7 shows the analysis of parameter estimates of the model.

Table 2.7. Analysis of Maximum Likelihood Parameter Estimates of the Model

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-1.36	0.32	-1.98	-0.73	17.98	<.0001
X	1	0.52	0.18	0.16	0.88	8.11	0.0044

The equation of the model is:

$$\widehat{Y}(x) = \widehat{\mu}(x) = e^{0.52X-1.36}$$

in which: $\hat{Y}(x) = \hat{\mu}(x)$ = Estimated TRIR and X is the Craft Worker Recruiting Difficulty Score in the project (0-4). The P-value of the model affirms its adequacy in demonstrating the association between two variables (P-value = 0.0044). The intercept parameter is also statistically significant at the 0.0001 level. Fig.2 shows the graph of the model which illustrates the exponential relationship between the craft worker recruiting difficulty and TRIR.
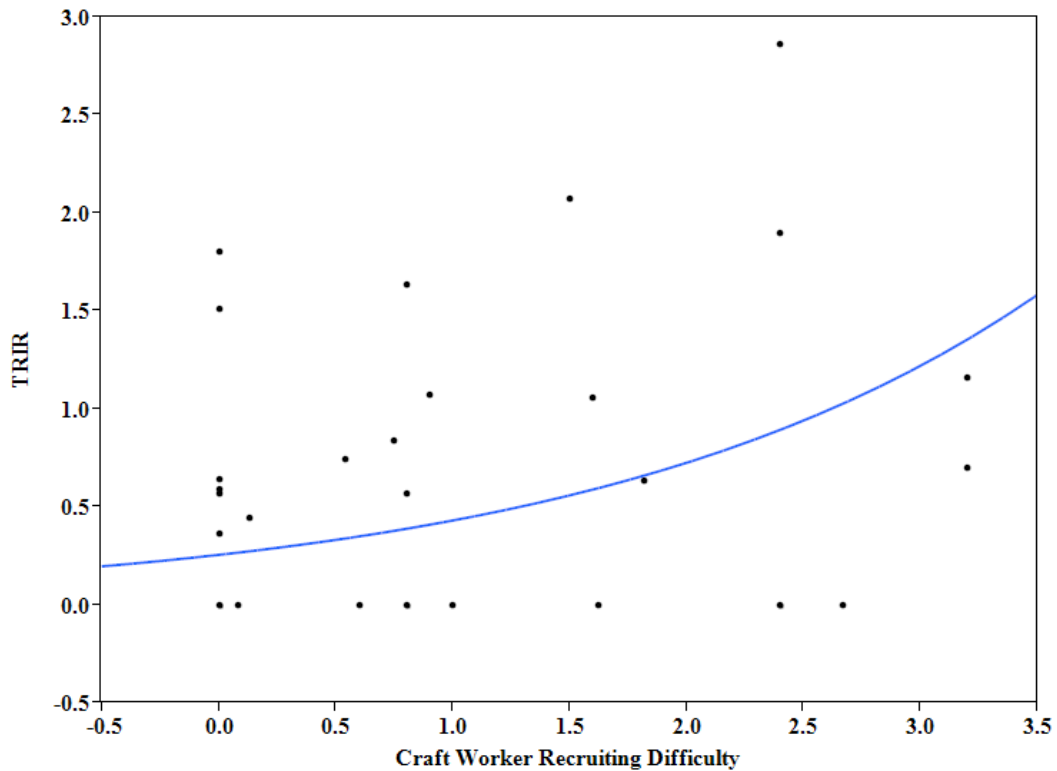
Figure 2. Poisson regression model of TRIR and Craft Worker Recruiting Difficulty

Goodness of Fit Test

The deviance, which compares the log-likelihood of the fitted values for any observation to the log-likelihood of the perfect fit, is the measure of discrepancy between the fit model and the data (Tutz, 2012). If the model with log-link contains an intercept term, the deviance equals (Tutz, 2012; Agresti, 2015):

$$D = 2 \sum y_i \, log \left(\frac{y_i}{\widehat{\mu}_i} \right)$$

Another alternative for assessing the goodness of fit of the Poisson regression model is the Pearson Statistics, which equals (Tutz, 2012; Agresti, 2015):

$$X_P^2 = \sum \left(\frac{y_i - \widehat{\mu}_i}{\widehat{\mu}_i} \right)^2$$

For a fixed number of n and increasing mean unboundedly, both D and X_P^2 have an approximately Chi-squared distribution with $n - p$ degrees of freedom where p is the dimension of the parameter vector (Agresti, 2015). Table 8 shows the result of the Chi-square test for the goodness of fit of the model. Since the result of the test is not statistically significant, the null hypothesis cannot be rejected which indicates that the data are consistent with the Poisson distribution. Therefore, it can be concluded that the model fitted reasonably well.

Table 2.8. Goodness of Fit of Poisson Regression Model

Goodness of Fit Statistic	Chi Square	DF	Prob >Chi Sq
Pearson	44.13	48	0.632
Deviance	40.38	48	0.773

Dispersion Test

The main feature of the Poisson distribution is that the mean μ is equal to the variance of the sample set. In the following equation, the σ^2 is the dispersion parameter of the Poisson model and is assumed constant (McCullagh and Nelder, 1983).

$$\mathbf{Var}\ (Y_i) = \sigma^2 E(Y_i) = \mu_i$$

McCullagh and Nelder (1983) argued that the dispersion parameter can be estimated by the following equation:

$$\sigma^2 = X_P^2 / (N - P) = \sum \left(\frac{y_i - \hat{\mu}_i}{\hat{\mu}_i} \right)^2 / (N - P)$$

in which X_P^2 is Pearson Chi-Square, N is the total number of data points and P is the dimension of parameter vector. $X_P^2 / (N - P)$ in the model is equal to 0.92 which indicates that the model does not have overdispersion and also has no significant underdispersion.

Studentized Deviance Residuals

Examining residuals of the model can be useful to identify where the Generalized Linear Model is fitted poorly and where unusual observation occurs (Agresti, 2015). The plot of Studentized Deviance Residual versus Predicted Response Variable (Y) is illustrated in Fig.3. The plot shows no pattern and all points are scattered randomly around the zero line. Moreover, there is no unusual observation in the residuals which indicates that there is no outlier in the dataset.
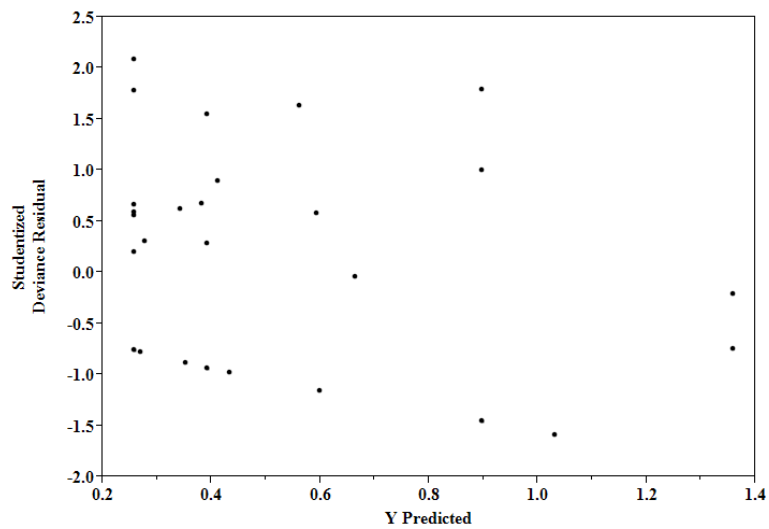
Figure 2.3. Studentized Deviance Residual vs. Predicted TRIR

95% Confidence Interval for Estimated TRIR

In Poisson distribution, all cumulants of Y are equal to μ. McCullagh and Nelder (1983) argued that if all cumulants are $O\ (n)$ and n tends to infinity, then

$$(Y - \mu)/\ k_2^{1/2} \sim N(0, 1) + O_p\ (n^{-1/2})$$

in which k_2 is the second cumulant of Y and is equal to μ. Since $n = 50$, the part of $O_p\ (n^{-1/2})$ becomes very small and can be reasonably neglected. Hence, the Y can be estimated with the normal distribution that has variance of μ ($\sigma^2 = \widehat{\mu}(x)$):

$$Y \sim N\ (\widehat{\mu}(x),\ \widehat{\mu}(x))$$

The 95% Confidence Interval (95% CI) for the response variable then can be calculated as:

$$95\%\ CI = \widehat{\mu}(x) \pm 1.96\sqrt{\widehat{\mu}(x)}$$

2.4.4. Comparison of Regression Models

The Poisson regression analysis was performed on each dataset of BM&M and RT-318 survey projects to examine the difference between two models. The result were two Poisson regression models which both demonstrated an aligned relationship between increased craft worker recruiting difficulty and increased TRIR. The 95% confidence interval for both coefficients of X and slope of the models were constructed. Since there was overlap between 95% CIs for each coefficient of X and slope from two models, it can be concluded that there is no statistically significant difference between two models. Table 9 shows the detail of this analysis.

Table 2.9. Comparison between Regression models of CII BM&M and RT-318 Survey dataset

Database	CII BM&M		RT-318 Survey	
Regression Model	$Y = e^{0.56X-1.40}$		$Y = e^{0.3X-1.1}$	
Parameter	Wald 95% Confidence Limits		Wald 95% Confidence Limits	
Intercept	-2.13	-0.68	-2.43	0.23
X1	0.17	0.94	-0.67	1.26

2.4.5. Summary of the Regression Analysis

Table 10 shows four levels of craft worker recruiting difficulty examined in the current work, expected TRIR, and the 95% confidence interval for each level. Since the lower bound of 95% confidence intervals for all levels was negative and negative values for TRIR is impossible, all lower bounds with negative values were set to zero. It also should be noted that because there is no project with recruiting difficulty score of more than 3.2 in the database, the regression model cannot provide estimation of TRIR for the very severe recruiting difficulty condition (score = 4).

Table 2.10. Expected TRIR and 95% CI under different recruiting difficulty circumstances

Craft Worker Recruiting Difficulty		TRIR	Lower 95% CI	Upper 95% CI
No difficulty	0	0.26	0	1.25
Slight	1	0.43	0	1.72
Moderate	2	0.73	0	2.39
Severe	3	1.22	0	3.39

2.5. Discussion

The result of the Mann-Whitney Test demonstrated the influence of craft worker shortage on the construction Total Recordable Incident Rate. The test proved that the distribution of TRIR in the projects that reported craft worker recruiting difficulty tends to be higher than the distribution of TRIR in projects that reported no craft worker recruiting difficulty. The T-Test analysis showed that the average TRIR in projects that reported craft worker recruiting difficulty was more than twice the average TRIR of projects that reported no recruiting difficulty (0.68 compared to 0.3). The average score of craft recruiting difficulty in the group of projects that reported craft shortage was 1.34, which falls between the slight and moderate level of craft worker shortage defined in Table 3. The significant difference in the average of TRIR between these two groups of projects indicates the substantial impact of the skilled craft worker availability on construction project Recordable Incident Rate.

This substantial impact was supported by the result of the Poisson regression analysis. The model demonstrated the exponential association between increased craft worker recruiting difficulty and increased TRIR. It showed that the shortage in skilled craft workers can result in a TRIR from 0.26 to 1.22, depending on the severity of the shortage. The model is statistically significant at the 0.01 level. It has reasonably good fit to the observed data and passed all diagnostic tests. The model is the first that contributes a statistically valid, quantified link between skilled craft worker availability and construction project safety performance.

The quantitative analyses presented herein indicate that an increase in safety incidents will occur during a skilled craft worker shortage in the construction industry. As identified by Taylor *et al.* (2016), the U.S. construction craft worker segment is experiencing structural changes, including: a workforce that is aging faster than all other private industries, national shortages in key industrial trades (e.g. welders, pipefitters, and electricians), and shrinking real wage gaps between construction craft workers and all other private industries. These challenges present significant changes to the construction industry as they increase the problem of skilled craft worker availability. As demonstrated in this study, the shortage not only has an impact on project cost and schedule performance, it will have significant negative impact on construction safety performance. While the industry may be willing to accept increased project costs and durations, the progress the industry has made in safety performance over the past 30 years makes any potential decrease in safety performance unacceptable.

2.5.1. Limitations of the model

While Table 10 provides the beneficial and statistically valid results, it is important to understand that the model is subject to the following limitations, primarily based on the sample dataset.

1) The tool's performance estimates are based on a sample of past projects performed between 2001 and 2014 in North America, therefore the model needs to be reviewed and updated from time to time.

2) The tool is based heavily on industrial projects and it is only based on projects performed in the U.S. and Canada, hence caution should be exercised when using the tool for projects outside of these regions.

3) The actual cost of the construction phase of the projects in the database ranges from $0.5M to $8,549M and the project duration ranges from 46 to 3,131 days. Therefore, it is recommended that the risk tool not be used for projects which fall outside these limits.

Further research is needed for projects which fall outside the cost and schedule characteristics presented in limitation 3. The operationalization of the model as a risk analysis tool is presented in CII (2015) and additional analysis detail is available in Taylor *et al*. (2016).

2.5.2. Practical Application of the Model

In a project that encounters shortages of craft workers, a tight schedule, overtime, and perceived work pressure by craft workers have been identified as the factors affecting construction site safety. When a project is executed by less qualified craft workers, increases in human errors, less familiarity with safety procedures and legislations, and inadequate safety training will be the factors that adversely influence safety performance. The model presented in this study serves as a valuable benchmark tool for project management teams to assess the safety risk in construction projects at the planning stage, with regard to the expected skilled craft worker availability. Based on the perceived risk and the type of craft worker problem (quality or quantity), the project management team can propose the proper mitigation strategies to prevent decline in safety performance. For example, if a project experiences craft shortage and consequently is on a tight schedule,

the manager can affect changes in perceived work pressure on craft workers by explicitly communicating the value of safety over expediency and keeping safety as the main priority in the project (Brown *et al*., 2000).

2.6. Conclusions

The research objectives of this study were to empirically examine the influence of craft worker shortage on construction safety performance. Data of 50 construction projects preformed in the U.S. and Canada between 2001 and 2014 were obtained from two databases and used to construct a larger database. A number of statistical analyses were performed to make sure there was no significant difference between projects in the two databases. In addition, since the two databases used different scales to measure craft worker availability, the scales were merged into a single measurement. The quantitative analysis of the skilled craft worker availability and Recordable Incident Rate of these 50 construction projects demonstrated that the average TRIR in projects that experienced craft worker recruiting difficulty was more than twice the average TRIR in projects that reported no craft recruiting difficulty. Furthermore, the result of Poisson regression analysis showed the exponential relationship between increased craft worker recruiting difficulty and increased TRIR in construction projects. The model represents the risk tool that links skilled worker availability to project safety performance.

This study's contribution to practitioners and the body of knowledge is the quantification of the influence of craft worker availability on construction project Incident Rate. Future research can focus on how to develop and adopt new innovative construction means and methods to account for working with a less qualified workforce, thus reducing the

possibility of human error. In general, the goal is to prevent the escalation of construction

safety incidents when skilled craft workers are not adequately available.

CHAPTER 3: Analysis of the Impact of Craft Labor Availability on North American Construction Project Productivity and Schedule Performance (Paper No.2)

Synopsis: The North American construction industry has experienced periods of craft shortages for decades. While this problem has received significant attention from researchers, less attention has been given to quantifying the impact of availability of craft labor on project performance. The primary contribution of the current work to the body of knowledge is the quantification of the relationship between craft labor availability and project performance, as measured by project productivity and schedule. Data from 97 construction projects completed in the U.S. and Canada between 2001 and 2014 were collected from two industry databases. The primary analysis shows that projects that experienced craft shortages underwent substantial and statistically lower productivity compared to projects that did not. The analysis also shows a significant growth in schedule overrun due to the craft labor shortages among the same population of projects. Further exploration by means of several regression analyses shows a statistically significant correlation between increased craft recruiting difficulty and lower project productivity and also higher schedule overruns in both project databases.

The results are confirmed across both databases and serve as informative models that provide valuable insight for project management teams to perceive the risk that lack of skills poses on project productivity and time performance. Understanding the level of impact that craft shortages are having through robust statistical analyses is a first step in

developing the motivation for industry leaders, communities, and construction stakeholders to address this challenge.

3.1. Introduction

A shortage of craft labor in the North American construction industry has been an unfortunate cyclic trend since the late 1980s. In 1983, the Business Roundtable forecasted that a shortage of skilled craft workers would hamper the growth of the construction industry by the late 1980s (BRT, 1983). In 1990, the Construction Industry Institute (CII) reported that a shortage of skilled labor already existed in some regions of the U.S. (CII, 1990). CII forecasted that this shortage would worsen through the 1990s partially due to demographic shifts. In 1997, the Business Roundtable confirmed the shortage by reporting that 60% of its surveyed U.S. construction companies experienced difficulties in recruiting and retaining their craft workforce (BRT, 1997). Later, a survey in the U.S. found that 78% of facility owners expressed that skilled labor shortage had increased during the past years (Rosenbaum, 2001). In 2007, 86% of the leading U.S. construction firms reported they were experiencing craft shortage on their recent performed projects (Sawyer and Rubin, 2007).

The 2008 U.S. recession was at least one period when the craft shortage temporarily improved, as witnessed by spikes in construction unemployment rates above 20% due to the work slowdowns (Construction Industry Institute, 2015). However, the current economic recovery period is once again experiencing craft shortages in some sectors of the U.S. construction industry. The U.S. Bureau of Labor Statistics (2013) predicted that the construction industry would be the fastest growing industry among goods-producing

sectors and third among all major industry sectors, with an annual growth rate of 2.6% and new job openings exceeding 1.6 million over the 2012-2022 period. Taylor et al. (2016) reported that the rapid economic recovery has already caused severe craft shortages in the U.S. Southeast and Southwest regions for specific craft skilled trades, including welders, pipe fitters, and electricians.

Construction is a labor-intensive industry and labor costs comprise a significant portion (30-50%) of the total actual cost of construction projects (McTague and Jergeas, 2002; Hanna et al., 2001). Therefore, the management of labor and productivity is a critical factor in the success of a construction project (Hanna et al., 2005; Ernzen and Schexnayder, 2000). On the other hand, the permeation of skilled labor shortages throughout the North American construction industry over the past decades has made the recruiting and retaining of skilled labors a major challenge, which can adversely affect overall project performance.

Craft labor shortages on a project are initiated by both the available quantity and/or qualification of craft labors. When project managers cannot hire the required quality levels of craft labor, the project is executed with less skilled workers, even if recruiting quantity needs are met. When craft labor quantity issues arise, a project cannot meet its basic labor demands.

Project cost, schedule, quality, and safety are the four primary measures of construction project performance. Previous work quantitatively analyzed the influence of skilled labor shortages on project safety performance and demonstrated a significant association between increased skilled labor recruiting difficulty and increased Occupational Safety and Health Administration (OSHA) Total Recordable Incident Rate (TRIR) (Karimi et al.,

2016). The current work examines the correlation between craft labor shortages and project productivity and also schedule performance as measured by total project time overrun.

3.2. The Impact of Craft Labor Availability on Productivity and Schedule Performance, Evidence from Previous Research

As craft workers are the major performers in executing the processes and activities in construction, they have a significant influence on labor productivity (Maloney, 1983). Labor productivity is a complex function of many factors which can increase and decrease project performance. For example, Dai et al (2005) identified 83 factors affecting construction labor productivity through analysis of focus group data. Wambeke et al. (2011) conducted a literature review and identified 50 individual factors affecting productivity and classified them under eight groups. However, in the majority of studies about productivity, the contribution of the availability of skilled labor on project productivity has been highlighted. Horner et al. (1989) conducted a survey among British contractors about labor productivity and ranked skill of labor as the most influential factor and quality of supervision as the third factor among 13 identified factors. Halligan et al. (1994) found that the unavailability of manpower is one of the most frequent cited factors in past literature as a cause of loss of productivity in construction projects. There are numerous recent research efforts that identified the significant impact of craft labor availability on project productivity mainly through analyzing construction professional opinion-based data. The lack of skill, experience and competency is recognized as the main labor-related factor that contribute to the loss of efficiency in projects encounter craft shortage. Table 1 summarizes the research methods and findings of these studies.

Table 3.1. Evidences of the impact of craft labor availability on construction project productivity in previous studies

Authors (Year)	Methodology	Summary of Results
Dai et al. (2009)	U.S. National wide survey on 2000 craft workers to assess the impact of 83 identified factors on labor productivity	Ten groups of factors that represent the underlying structure of the productivity were identified. Four factors were related to labor issues: Training, Craft worker qualification, Superintendent competency, and Foreman competency. The other factors were construction equipment, materials, tools and consumables, engineering drawing management, direction and coordination, and project management. In addition, craft worker qualification was identified as one of the three areas with the greatest possibility for project productivity improvement. The other two factors were construction equipment and project management.
Roja and Aramvareekul (2003)	Survey of U.S. based owners, consultants, general contractors to identify the relative importance of factors influencing labor productivity	The factor category of Manpower was ranked as the 2nd most influential on labor productivity among four factor categories. This factor includes experience, activity training, education, motivation, and seniority. The three other factors were management systems (ranked 1st), industry environment, and external conditions.
Liberda et al. (2003)	Interview with Canadian construction professionals to identify and prioritize the productivity factors	"The worker experience and skills" was ranked the 2nd most critical factor among 51 identified factors.
Chang et al. (2007)	Quantifying the impact of schedule	There was a statistically significant relationship between the two ratios of "actual

	compression on labor productivity in 103 U.S. based mechanical and sheet metal projects	number of manpower at peak / estimated one" and also "actual average manpower/ estimated one" and the loss of productivity in projects (Pearson correlation = 0.398 and 0.351 respectively). These two variables can be interpreted as the level of shortage experienced in a project.
Lim and Alum (1995)	Survey among contractors in Singapore about factor affecting construction productivity	Difficulty in recruitment of supervisors and workers were the 1st and 2nd most important factors among 17 identified factors.
El-Gohary and Aziz (2014)	Survey among 489 Egyptian contractors, consultants and owners	Labor experience and skill was ranked the first and most critical factor affecting construction productivity among 30 identified factors. In addition, competency of labor supervisor ranked 5th among all factors.

In addition to the lack of skills, experience and competency, extended overtime also can have substantial impact on productivity. Projects experiencing a shortage of skilled craft workers may also have a tight scheduling in order to meet a project deadline. Hanna et al. (2005) identified that overtime scheduling has become the prevalent option in this situation as it accelerates a project schedule and also an associated premium pay with overtime can attract the required workforce to complete the project.

Thomas (1992) conducted a literature review on the effect of scheduled overtime on labor productivity. He argued that because the factors affecting labor productivity are numerous, it is not easy to determine the significance of overtime impact on labor productivity. Although the study concludes that the literature on this impact was sparse, it revealed that there has been a general consistency in literature on overall loss of efficiency due to the scheduled overtime. Similarly, Halligan et al. (1994) believe that extent of the productivity

loss due to overtime can vary from project to project. They argued that the losses are mostly due to the fatigue and decrease in labor motivation, therefore, the impact of overtime on labor motivation can be lessened by effective management. Thomas and Raynar (1997) found that scheduled overtime can result in a loss of productivity. They argued the losses were due to the inability to provide material, tools, equipment and information at an accelerated work. Lyneis and Ford (2007) found that the use of overtime can have significant negative impacts on productivity. Furthermore, Hanna et al. (2005) developed a quantitative model that estimates a loss of work hours due to inefficiency caused by overtime. El-Gohary and Aziz (2014) on the survey among construction companies in Egypt, ranked overtime as the 18th factor among 30 ones that affecting labor productivity. In summary, the past literature provides a consistent message that the impact of overtime on project productivity is considerable.

The benefits of studying overtime in the construction industry is twofold. First, it illuminates one of the possible reasons behind the loss of efficiency when there is a craft shortage in a project. Second, it is the impact of craft labor availability on schedule performance. There has been a general belief among some practitioners that they can manage project schedule performance effectively and eliminate an expected project delay with overtime when encountering a shortage of skilled labor. This study also examines whether the shortage of craft labor has significant impact on project schedule performance and whether overtime can eliminate the expected delay.

Baldwin and Manthei (1971) conducted one of the earlier studies that examined the causes of delays on U.S. construction projects. They recognized the labor supply and lack of skills in craftsmen as two factors contributing to construction delay. Arditi et al. (1985)

investigated construction projects completed in Turkey and reported the shortage of qualified workers as one of the main causes of delays. Following these two earlier studies, several researchers examined the impact of craft labor shortages on project performance through the collection of expert practitioner opinion-based data. The lack of construction labor has been identified as one of the most critical factors in the majority of these studies conducted over the past decades in various countries and on different types of construction projects (Toor and Ogunlana, 2008). Table 2 shows the summary of the research methods as well as the main result of these studies. The studies demonstrate strong qualitative support for the influence of craft workforce issues on schedule performance mainly by identifying the rank of related factors among a pool of identified factors. Inadequate supply of labor, shortage of skilled workers, and low productivity of labor and supervisors have been recognized as three labor-related factors contributing to schedule overruns in construction projects.

Table 3.2. Literature on the impact of craft labor availability on construction project schedule performance in previous studies

Authors (Year)	Methodology	Summary of results
Wambeke et al. (2011)	Survey of 260 U.S. construction companies about causes of variations in tasks starting time and duration	Project managers ranked "worker lack of skills/experience to perform the tasks" as the 4th leading cause of task duration variation among 50 identified factors. Overall, when also including the attitude of labor and foremen, this cause was ranked as the 7th factor. Labor force capability is also identified in the top nine factors that account for 79% of the overall variance of the task duration variations.
Abdul-Rahmaan et al. (2006)	Survey followed by interview among Malaysian clients,	Labor shortages and lack of skills were identified as the 2nd most important major causes of delay in construction projects.

	consultants, and contractors about delays in construction projects	
Toor and Ogunlana (2008)	Survey among 80 managers about delays in major construction projects in Thailand	Poor efficiency of supervisor and foreman were ranked as 10th, and unavailability of local labor as the 35th factors among 75 main problems causing delay in the major construction projects.
Kaming et al. (1997)	Interview with project managers working in high-rise construction projects in Indonesia	Labor productivity and skilled labor availability were ranked as the 2nd and 7th variables among 8 identified variables of time control.
Arditi et al. (1985)	Survey among Turkish public agencies and contractors	Shortage of qualified workers was ranked as the 6th among 8 main reasons for construction delays.
Assaf et al. (2006)	Survey among contractors, consultant and owners' firms in Saudi Arabia	Owners ranked shortage of labors and unqualified workforce as the 1st and 2nd most important cause of delay among 73 identified factors. The consultants ranked shortage of labors as the second important factor. Overall, the group of labor-related factors was ranked 4th among 9 groups of factors by all three groups of participants. The labor-related factors include shortage of labors, unqualified workforce, low productivity of labor, personal conflict among labor, and nationality of labors.

In summary, the body of literature provides strong qualitative evidences for the following influential relationships: 1) a negative impact of a lack of skills, experience and competency on project productivity performance, 2) an adverse impact of shortage in skilled labor and supervisors and also low productivity of craft labor and supervisors on project schedule performance. The literature also provides quantitative evidence of the negative impact of scheduled overtime on project productivity. However, the evidence of

using more overtime when there is craft shortage in a project is limited to the opinion-based data. While the past literature provides wealth of information about these causal relationships, no studies have quantitatively examined the impact of craft labor availability on project productivity and schedule overrun. The current work contributes to the existing body of knowledge by collecting and analyzing empirical data of craft labor availability, labor productivity, and schedule performance of recently completed projects in the North America to quantify the impact of a craft labor shortage on project productivity as well as schedule performance.

To accomplish this goal, two research objectives were defined: 1) To identify whether there is a significant difference in productivity and time overrun of projects that experienced a craft labor shortage versus those that did not; 2) To identify whether there is a significant relationship between craft labor recruiting difficulty and construction productivity and also actual schedule growth in construction projects. 3) To identify whether there is a significant relationship between craft labor recruiting difficulty and higher usage of overtime hours in projects. The last objective coupled with two other objectives can help to better elucidate the influence of shortage of skills on project productivity and, in particular, on project schedule performance.

3.3. Research Methods

3.3.1. Data Source

The data used in this research were obtained from two different databases, which were analyzed separately to validate the results as well as to enhance the reliability and validity of the study. The first source was a primary data collection effort through a Construction

Industry Institute (CII) Research Team 318 (RT-318) survey. This survey collected project performance and workforce demographic data on completed construction projects in the U.S. and Canada. The survey was developed, pilot tested, and distributed to the CII and non-CII member construction organizations. There were 29 total responses to the survey, with 26 projects from the U.S. and three from Canada. The majority of survey responses involved heavy industrial projects (25 out of 29) while the remaining projects were building (one project), light industrial (one project), and infrastructure (two projects). Seventeen projects used non-union labor (59%), 7 used union labors (24%) and 5 used a combination of both options (17%) to staff their craft workforce. The projects were distributed across North America covering 18 states in the U.S. and 3 Canadian provinces. All projects were performed and completed between 2007 and 2014.

The second data source was obtained through the Construction Industry Institute (CII) Benchmarking and Metrics (CII BM&M) database. The CII BM&M database was designed to capture comprehensive data of construction projects performed by CII member companies. For the purpose of this research, the projects in this database that reported data related to the availability of craft workers were selected. This subset consisted of 68 completed projects of which 59 were performed in the U.S. and nine in Canada. Out of these projects, 31 projects (46%) were heavy industrial, 24 projects (35%) were building, seven projects (10%) were light industrial and six projects (9%) were infrastructure projects. All projects in this database were performed and completed between 2001 and 2013. Table 3 shows the average, median, and range of the size of projects in terms of actual cost, actual time, and actual craft direct work hours in both databases.

Table 3.3. Summary of projects size in RT-318 Survey and CII BM&M Database

Database	Project Size	Average (Median)	Min, Max
RT-318 Survey (29 projects)	Actual Cost ($M)	455.15 (45)	3.6, 8549
	Actual Schedule (Day)	554.65 (533)	134, 1648
	Craft Work Hour (1000 hr.)	610.63 (321)	13.3, 3777.9
CII BM&M (68 projects)	Actual Cost ($M)	142.49 (40.1)	0.5, 1799.3
	Actual Schedule (Day)	1054.48 (678)	46, 3131
	Craft Work Hour (1000 hr.)	732.5 (110)	2.5, 8870.6

3.3.2. Skilled Labor Availability Measurement

In both databases, an estimate of the level of craft shortage in projects relied on subjective evaluations of the project management team. The major benefit of this procedure was to compensate for the deficiency in the quantitative data for different trades in the RT-318 projects and also the absence of quantitative data for different trades in the BM&M projects. Although the data were obtained on two different scales, in this manner, the results of analysis on two databases were comparable.

In the RT-318 survey, the respondents were asked to indicate whether their project was impacted by a craft labor shortage. Furthermore, they were asked to indicate the level of craft recruiting difficulty they experienced on their project for 13 craft labor trades, which included carpenter, pipefitter, electrician, boilermaker, sheet metal, ironworker, pipe welder, structural welder, equipment operator, crane operator, millwright, instrument fitter, and supervisors. There were five levels of recruiting difficulty defined in the survey ranging from No Difficulty to Very Severe (Table 4).

Table 3.4. Levels of craft recruiting difficulties in the RT-318 survey

Level	Definition	Score
No difficulty	There was no shortage. Able to staff the project with no delay on construction	0
Slight	Recruiting difficulties led to consumption of schedule float and/or contingency	1
Moderate	Recruiting difficulties led to delay of completing project activities on time	2
Severe	Recruiting difficulties led to delay of completing project milestones	3
Very Severe	Recruiting difficulties led to project delay	4

To provide an overall level of craft recruiting difficulty for each project, the authors calculated an aggregate average of craft recruiting difficulty across these 13 trades for each project as:

$$\text{Craft recruiting difficulty score of a project} = \frac{(0 \times A) + (1 \times B) + (2 \times C) + (3 \times D) + (4 \times E)}{13}$$

Eqn. (1)

in which A, B, C, D, and E are the number of trades in each level of recruiting difficulty from No difficulty to Very severe.

In the CII BM&M database, the respondents indicated the level of availability of skilled labor across all trades compared to what had been specified during the planning stage of their project. These levels ranged from Extremely Negative (-5) to Extremely Positive (+5), and Zero represents an "As Planned" situation.

3.3.3. Productivity Observations

For each project in the RT-318 survey database, the productivity Performance Factor (PF) was calculated, which is the ratio between estimated and actual total craftwork hours in a project (Equation 2). This index can be used to show the relative labor productivity of a project (Hanna et al., 2005). The PF is defined as:

$$\text{Performance Factor (PF)} = \frac{\text{Estimated Total Craft Work Hours}}{\text{Actual Total Craft Work Hours}}$$

Eqn. (2)

A PF of 1 means a project was constructed using the exact number of estimated total craft work hours. A PF<1 represents a project that required more total craft work hours than estimated to reach completion, while a PF>1 represents a more productive project as it was completed with fewer craft work hours than planned. In general, a higher PF demonstrates a project completed with a higher level of workforce productivity. The advantage of PF over other productivity measurements that use direct unit rates is that it can be easily obtained for a project which contains different units of output (Construction Industry Institute, 2013). However, PF does not provide the actual productivity of various activities and can only be used to compare relative project productivity.

In the CII BM&M database, the respondents indicated the level of overall perceived construction productivity compared to what was expected at the planning stage of a project. These levels range from an "Extremely Negative" (-5) to an "Extremely Positive" (+5), and Zero represents an "As Planned" situation. This type of subjective evaluation, which is based on the experienced judgment of the project management team, provides a holistic picture of overall project productivity. In this manner, and with regards to the absence of a

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universal standard definition of productivity in the U.S. construction industry (Nasir et al., 2014, Park et al., 2005), the various productivity measurements in different trades will be taken into consideration. However, such a perceived observation of a site's productivity is not ideal, and the authors acknowledge this as a weakness of the study.

3.3.4. Schedule Performance

The schedule performance in both databases was measured by the percentage of schedule overrun relative to the planned construction schedule (Equation. 3):

$$\text{Schedule Overrun (\%)} = \frac{\text{Actual Schedule} - \text{Planned Schedule}}{\text{Planned Schedule}} \times 100$$

Eqn. (3)

In addition, in the CII BM&M database the respondents were also asked to indicate the level of success of their project's schedule performance on the scale of 1 as "not at all successful" to 7 as "extremely successful". The project managers responded to this question with regard to the actual project's circumstances which may include some unforeseen problems (e.g. unforeseen labor shortage, etc.) and overall, evaluated the schedule performance of a project. Therefore, any association between this measurement and a predictor variable can be considered as an indication of its significant influence on schedule performance. Although this measurement relies on a subjective assessment, its strength lies upon the project management team's judgement.

Schedule performance like other project performance parameters has several intervening variables such as changes in scope, change order, and weather etc. To take into

consideration of these variables in analysis, two appropriate statistical analysis methods, t-test and regression, were selected.

3.4. Data Analysis

3.4.1. Hypothesis Development

As explained earlier, the respondents of the RT-318 survey were asked whether their projects were impacted by a craft labor shortage. Therefore, the projects in this database can be divided into two groups of: 1) project impacted by craft labor shortage and 2) projects not impacted by a craft labor shortage. The projects in the CII BM&M also were divided into two groups: 1) projects with a skilled labor availability score of less than zero (score<0), which are classified as projects that experienced some level of skilled recruiting difficulty; and 2) projects with a score of equal or greater than zero (score≥0), which are classified as projects that did not experience skilled labor recruiting difficulty. The CII BM&M questionnaire defined the zero score as a situation where actual skilled labor availability was similar to what was expected during project planning (i.e. skilled labor availability did not positively or negatively impact project performance when compared with the project plan) and scores greater than zero as the condition where the availability of craft workers had a positive impact on project performance. Therefore, it can be reasonably assumed that when a project in this database has a score of equal or greater than zero, the project experienced no craft recruiting difficulty while projects with scores between -1 to -5 experienced some level of skilled labor shortage. To determine the significance of the impact of a craft labor shortage on project productivity and schedule

performance, the following hypotheses were developed: 1) the mean productivity in projects that experienced a craft labor shortage is lower compared to projects not experiencing a craft labor shortage, and 2) the mean time overrun in projects that experienced a craft labor shortage is higher compared to projects not experiencing a craft labor shortage. All hypotheses are described in detail in Table 5.

Table 3.5. Summary of Hypothesis Development

Projects Classification	Database	Null Hypothesis	Alternative Hypothesis
H1: projects impacted by craft shortage vs. not impacted	RT-318 Survey	There is no difference in mean productivity.	The mean productivity is higher in projects not impacted by craft shortage.
H2: projects impacted by craft shortage vs. not impacted	RT-318 Survey	There is no difference in mean time overrun.	The mean time overrun is higher in projects impacted by craft shortage.
H3: projects with availability of labor score <0 vs. score≥ 0	CII BM&M	There is no difference in mean productivity.	The mean productivity is higher in projects with score ≥ 0.
H4: projects with availability of labor score <0 vs. score≥ 0	CII BM&M	There is no difference in mean time overrun.	The mean time overrun is higher in projects with score <0.

A t-test was conducted to compare the average of productivity and time overrun between the two groups of projects in each database and to determine if the differences were statistically significant. Shapiro–Wilk statistics were examined to test the normality assumption of each group. If the Shapiro–Wilk statistics is not significant, the null hypothesis, which asserts the normal distribution of data points, cannot be rejected. The result indicated that probability values of the test for H1, H2 and H3 were greater than 0.05 which means the normality assumption of the t-test was satisfied for these hypotheses. The

test was significant at the 0.05 level for H4. However, since the t-test is robust to the violation of normality assumption, particularly when data points are more than 30 (Agresti and Finlay, 2009) and n=47 for H4, the result of the test for H4 is also accurate. The Levene's test was also performed to examine the assumption of equality of variance. The results of the test show that this assumption was satisfied, as they were not significant at the 0.05 level except for H3. For this hypothesis (H3), therefore the test was performed assuming the unequal variance. As shown in Table 4, the average time overrun in the RT-318 survey projects that were impacted by a craft labor shortage was 29.17% compared to 4.49% for projects not impacted by a craft labor shortage. Furthermore, the average project productivity factor (PF) in projects that experienced a craft labor shortage was 0.84 compared to 1.03 for projects that did not experience a craft labor shortage. The p-values in both tests (0.031, 0.044) were less than 0.05, which resulted in rejection of both null hypotheses (H1, H2), and allowed us to conclude that productivity and schedule performance were negatively impacted by lack of skilled labor availability.

Table 3.6. Hypothesis testing result for time overrun and productivity comparison

(RT-318 survey projects)

Performance Parameters	Projects impacted by craft shortage			Projects not impacted by craft shortage			Levene's	T	Df	P
	Mean	N	W	Mean	N	W	F			
(H1) Productivity Factor (Eqn. 2)	0.84	12	0.97*[1]	1.03	9	0.9*[1]	0.23*[2]	1.8	19	0.044
(H2) Time Overrun (Eqn. 3)	29.17	12	0.88*[1]	4.49	11	0.96*[1]	0.48*[2]	1.98	21	0.031

In the CII BM&M projects, the average perceived construction productivity factor in projects with a craft availability score of less than zero was -1.05 while the average for projects that experienced no skilled labor recruiting difficulty was 0.89. The p-value of the test was less than 0.000 affirming that project productivity is significantly impacted by a skilled labor shortage. The average time overrun in projects with some level of labor recruiting difficulty was 13.7% while the average for projects that experienced no skilled labor recruiting difficulty was 2.99% (Table 7). The p-value of 0.047 again indicated the rejection of the null hypothesis (H4), and allowed us to conclude that the greater time overrun in projects with craft labor shortage is statistically significant at the 0.05 level.

Table 3.7. Hypothesis testing result for time overrun and productivity comparison in CII BM&M projects

Performance Parameters	Craft availability score < 0			Craft availability score ≥ 0			Levene's	T	Df	P
	Mean	N	W	Mean	N	W	F			
(H3) Construction Productivity Factor	-1.05	20	0.97*[1]	0.89	47	0.93*[2]	1.27*[3]	3.81	65	0.000
(H4) Time Overrun (Eqn. 3)	13.7	14	0.91*[1]	2.99	37	0.96*[1]	10.19*[4]	1.78	15.6	0.047

W: Shapiro–Wilk Statistics

*[1] = Not Significant at 0.05 level (Normality assumption was satisfied)

*[2] = Significant at 0.05 level (N=47>30 so the test is robust)

*[3] = Not Significant at 0.05 level (Equality of variance assumption was satisfied)

*[4] = Significant at 0.05 level (Unequal variance is assumed)

The analyses of hypothesis testing demonstrate the substantial influence of skilled labor recruiting difficulty on project schedule performance and productivity. The results justify a deeper exploration on these influential relationships in construction projects.

3.4.2. Regression Analysis

To further examine the influence of craft labor availability on project productivity and schedule performance, a number of simple linear regression analyses were performed on each database. The two main variables used in the regression analyses to assess the level of craft labor availability were the craft recruiting difficulty variable (RT-318 survey) and the skilled labor availability variable (CII BM&M). Both of these two variables are categorical with natural ordering, so they can be referred to as ordinal variables. In order to use more powerful methods available for quantitative variables such as regression, it is possible to assign numerical scores to categories of ordinal variables and treat them as an interval variable (Agresti and Finlay, 2009). As shown earlier, both of these variables were assigned numerical scores and were suitable to be used in regression analysis. The other variables are either quantitative variables (e.g. time overrun, PF, percentage of time overtime hour) or have similar status as skilled labor availability variables (e.g. meeting schedule expectation, construction productivity factor in BM&M database). For all regression analyses, outliers have been detected and removed from the analysis using the Cook's distance, as suggested by Agresti (2015). The null hypothesis for each analysis was that no relationship existed between two variables. The alternative hypothesis was that there is a relationship between the two variables, which was determined by obtaining the p-value of less than 0.05.

3.4.2.1. Impact of Skilled Labor Availability on Construction Productivity (RT-318 Database)

As shown in Table 4, the craft recruiting difficulty variable was used to measure the level of craft labor shortage in RT-318 projects. The minimum score in this database was zero and the maximum score was 2.67, which refers to the craft recruiting difficulty level close to the severe condition. The first regression analysis was performed to examine the relationship between craft recruiting difficulty and project productivity. The total number of projects in this analysis was 20 projects. The analysis shows the linear association between increased craft recruiting difficulty and a decreased productivity factor. The p-value of 0.005 resulted in rejection of the null hypothesis and conclusion that there was a significant influence of craft labor shortage on project labor productivity. The R^2 value of the equation is 0.36. Fig.1 shows the regression model.
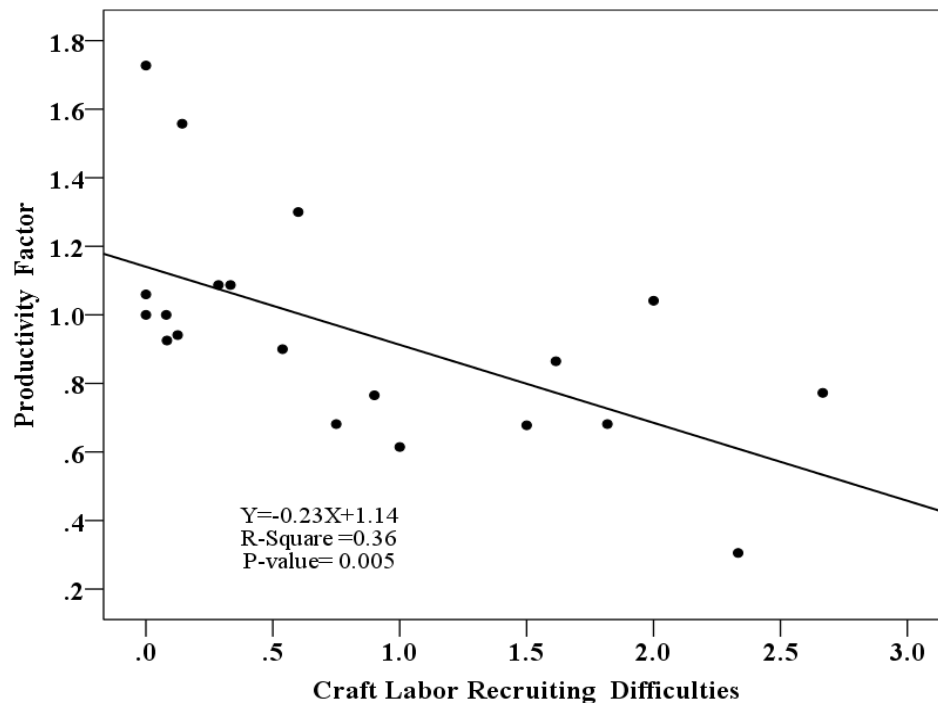
Fig. 3.1. Regression analysis of the Craft labor recruiting difficulty and Productivity Factor (RT-318 database)

CII BM&M Database

The next regression analysis was performed between the skilled labor availability variable and the construction productivity factor in the BM&M database. The skilled labor availability score was the variable that measured the level of craft availability in CII BM&M projects. The difference between this variable and the one in the RT-318 database is that this score also provides the measure for the situation that availability of craft labor had positive impact on projects (score = 1 to 5) compared to what has been specified in a project's original plan. This condition may be referred to when there is a surplus of skilled labor in a project labor market.

The total available data points for this analysis was 67. The analysis shows that lower availability of skilled labor resulted in lower overall construction productivity. In addition, the analysis demonstrates that a surplus in the skilled labor market resulted in higher project productivity, compared to what has been expected in the planning stage. The p-value of the model was 0.000 which indicated the adequacy of the model. The R^2 value of the model was 0.43. The model shows that the perception of project managers toward overall project productivity was significantly associated with their perception about the availability of skilled labor. The model can be observed in Fig.2.
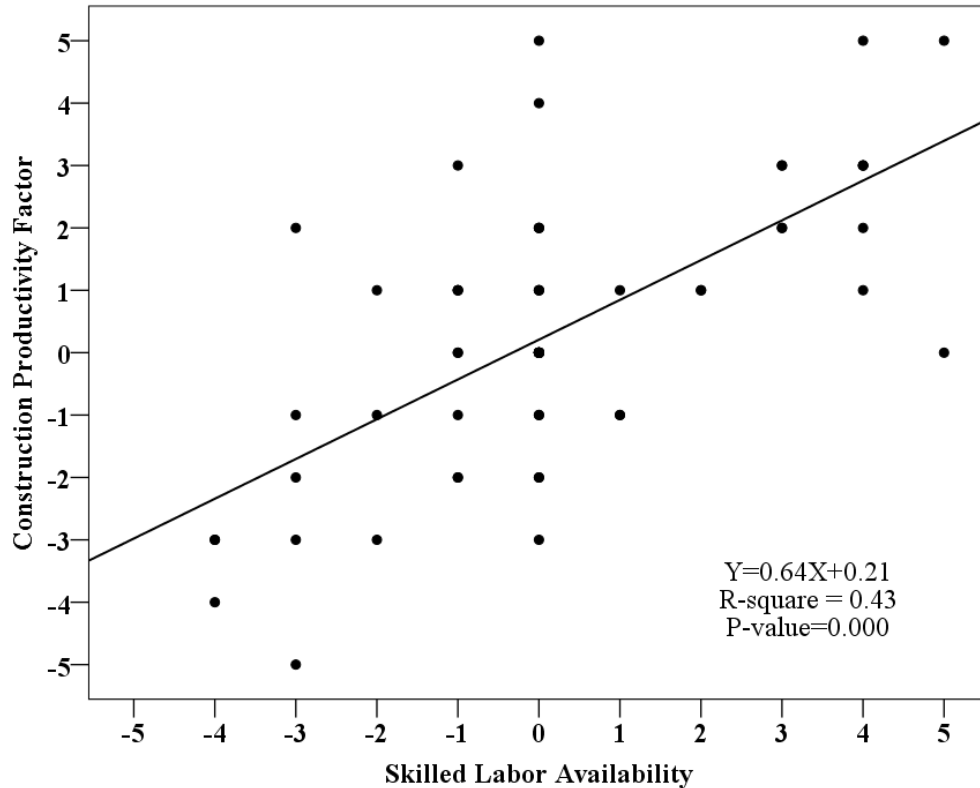
Fig. 3.2. Regression analysis of the Skilled Labor Availability and Construction Productivity Factor (CII BM&M database)

3.4.2.2. Impact of Skilled Labor Availability on Schedule Performance (RT-318 Database)

The next analysis was performed to examine whether there is an association between skilled labor availability and time performance. The total available data points for this analysis was 24, which was reduced to 19 projects after removing the outliers. As illustrated in Fig. 3, the regression analysis shows the positive relationship between increased craft recruiting difficulty and increased time overrun. The p-value of the equation is 0.044 which indicates the significance of the relationship. The R^2 value of the equation is 0.22 which means that 22% of the variation in time overrun in this set of projects can be explained by the craft recruiting difficulty variable.
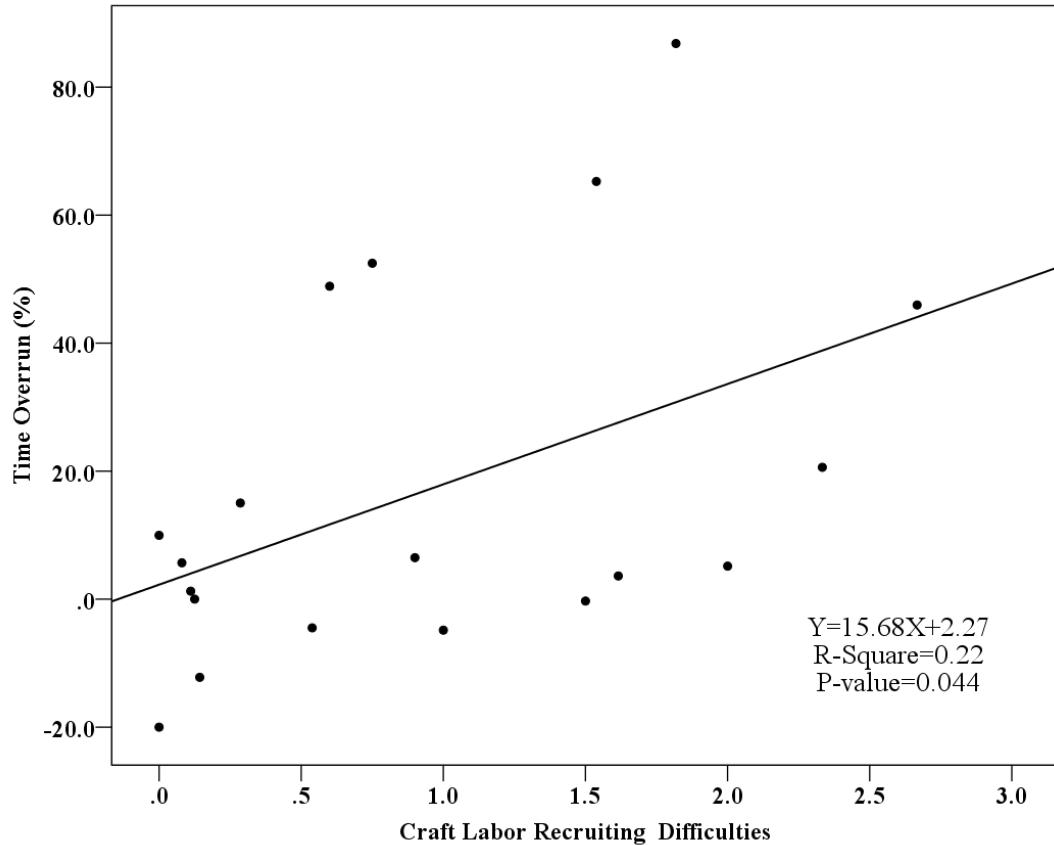
Fig. 3.3. Regression analysis of Craft labor recruiting difficulty and Time overrun

(RT-318 database)

CII BM&M Database

The total number of data points for this analysis was 58 which was reduced to 51 projects after removing outliers. The regression analysis shows the linear relationship between skilled labor availability and time overrun. It demonstrates that increased time overrun was associated with decreased availability of skilled labors. Interestingly, the analysis also shows that there was a decrease in time overrun when there was a surplus in skilled labor availability. The p-value of 0.043 resulted in rejection of the null hypothesis and the conclusion that skilled labor availability is associated with time overrun. However, the low

R^2 value of 0.09 indicated that this variable can only explain about 9% of time overrun variation in these set of projects. In subsequent analysis, the authors sought to explain this statistically significant but relatively weak influential relationship. The model can be observed in Fig.4.
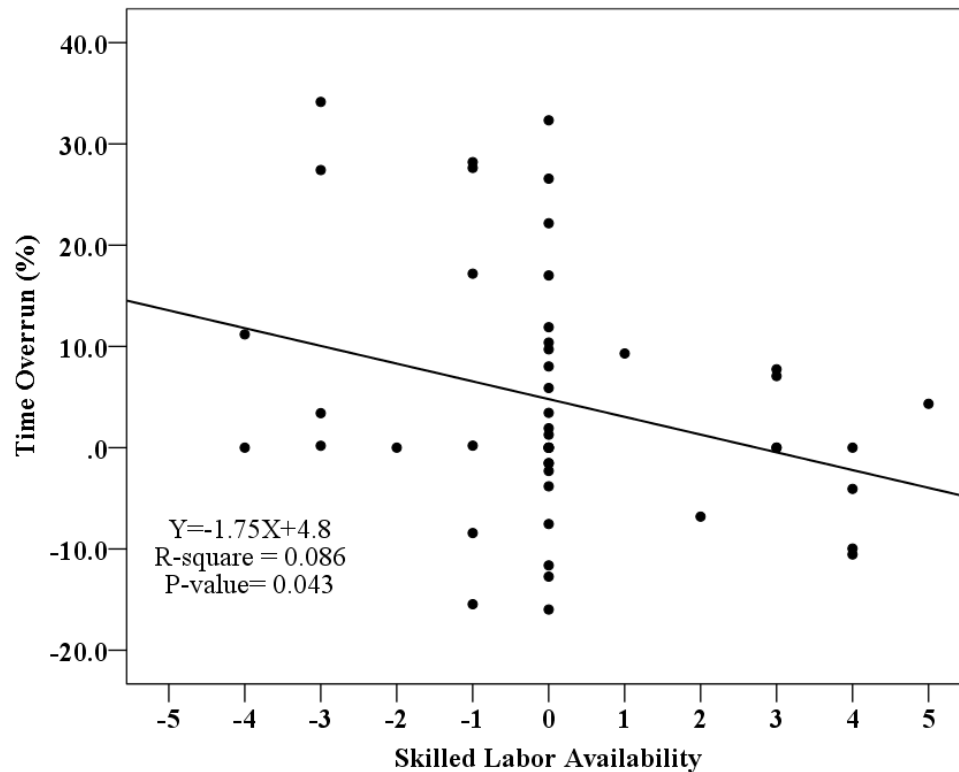
Fig. 3.4. Regression analysis of the Skilled Labor Availability and Time Overrun

(CII BM&M database)

The authors also examined the influence of skilled labor availability on the overall perception of the project management team toward the success in meeting schedule performance expectations. The total available data points for this analysis was 55 which was reduced to the 53 projects after removing two outliers. The analysis shows that lower availability of skilled labor resulted in lower success in meeting a schedule performance

expectation. The p-value of the model was 0.004 which indicated the adequacy of the model. The R^2 value of the model was 0.15. This model reaffirms the result from the previous regression analysis that indicates the statistically significant association between craft labor recruiting difficulty and time overrun. The model can be seen in Fig.5.

Y=0.23X+5.75
R-square = 0.15
P-value= 0.004
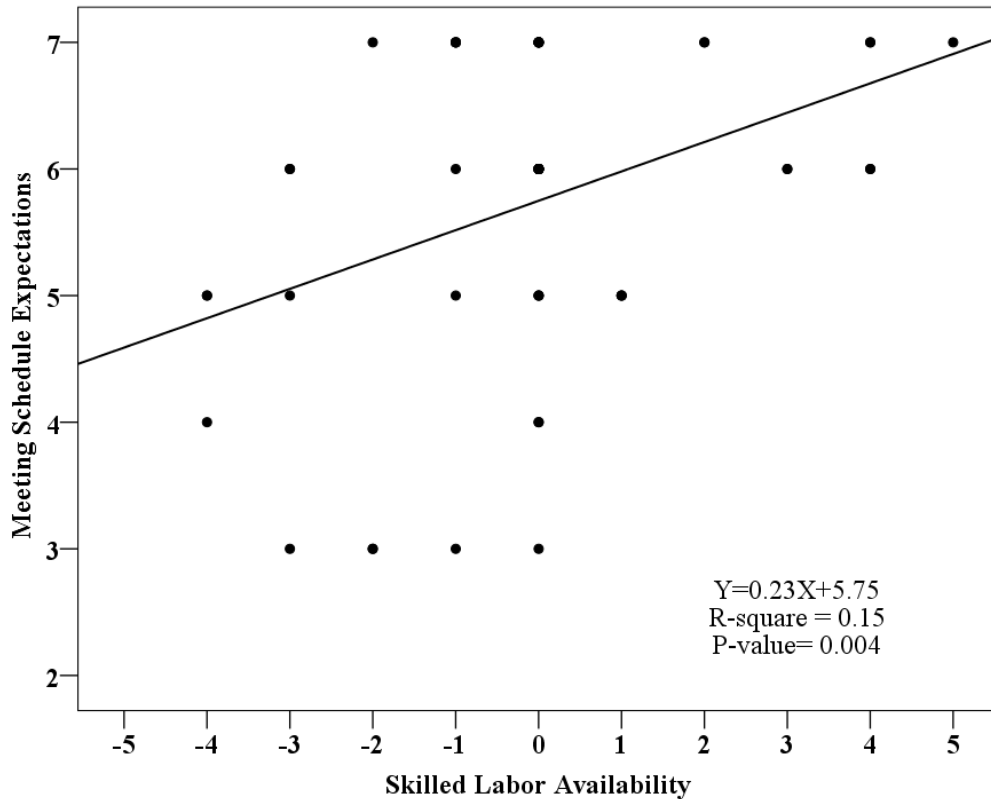
Fig. 3.5. Regression analysis of the Skilled Labor Availability and Meeting Schedule Performance Expectations (CII BM&M database)

3.4.2.3. Relationship between Skilled Labor Availability and Overtime

The next analysis examined whether projects with a higher level of skilled labor shortage tend to use more overtime. The total number of projects reporting overtime data in the CII BM&M database was 30 projects, with 8 projects that had a skilled labor availability score of less than zero and 22 projects with a score equal or greater than zero. The questionnaire

defined overtime percentage hour as the ratio of work hours performed above 40 work hours per week to the total work hours. With the exception of one project, all projects used extended overtime ranging from 1% to 35% of the total craft work hour. However, the average of percentage overtime hours used in projects experiencing craft labor shortages was 19.7% compared to 13.6% for projects did not experience craft shortages. After detecting and removing one outlier in the data points, the regression analysis was performed between two aforementioned variables. The analysis returned a linear equation that demonstrated the lower level of availability in skilled labors was associated with a higher percentage of overtime hours in projects. The p-value of 0.034 resulted in rejection of the null hypothesis. The R^2 value of the equation was 0.16. The model can be seen in Fig.6.

The figure shows a scatter plot with the equation Y=-2.16X+16.23, R-square = 0.16, P-value= 0.034. The x-axis is labeled "Skilled Labor Availability" and the y-axis is labeled "Percentage of Overtime Hours (%)".
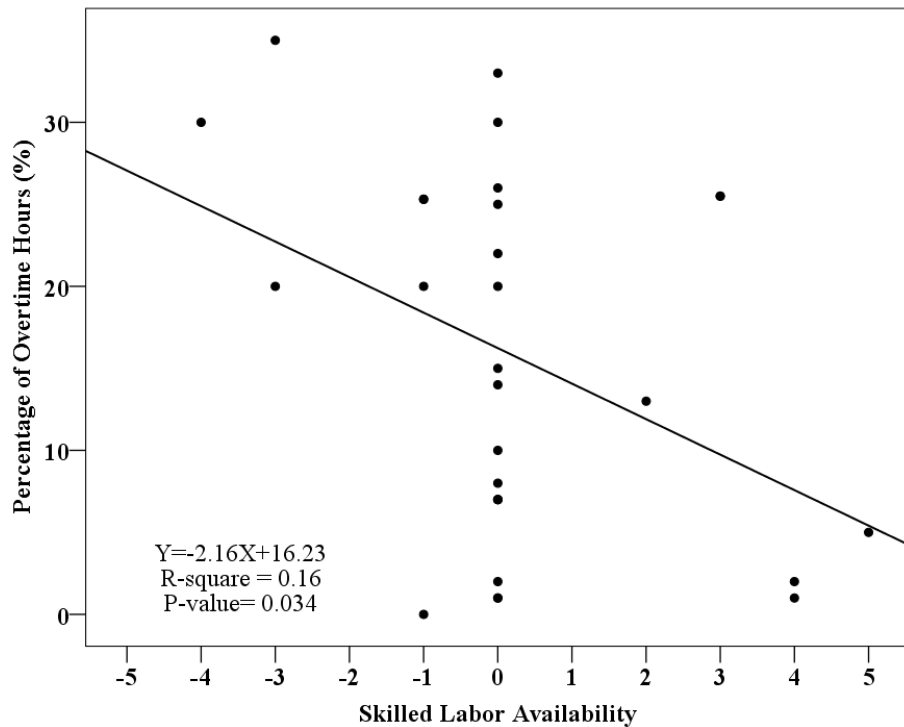
Fig. 3.6. Regression analysis of the Skilled Labor Availability and Percentage of Overtime Hours (CII BM&M database)

3.4.2.4. Impact of decline in Productivity on Schedule Performance

The last analysis was on the relationship between decline in productivity and schedule overrun in both databases. In RT-318 survey projects, the total number of available data points was 22 which reduced to 17 after detecting and removing 5 outliers. The regression analysis between Productivity factor (PF) and Time overturn returned a linear equation that shows the decline in productivity is associated with increased in time overrun (Time overrun=44.3 - 29.8 × PF). However, this relationship is not significant (p-value= 0.23) neither strong (R^2=0.09).

In the CII BM&M database, the total number of available data points was 58. After detecting and removing 3 outliers, it reduced to 55. The regression analysis shows the lower productivity would result in higher time overrun. The p-value of 0.012 resulted in rejection of null hypothesis. The R^2 value of the equation was 0.11. The analysis shows the statistically significant but relatively weak relationship between productivity and time overturn. The model can be observed in Fig.7.
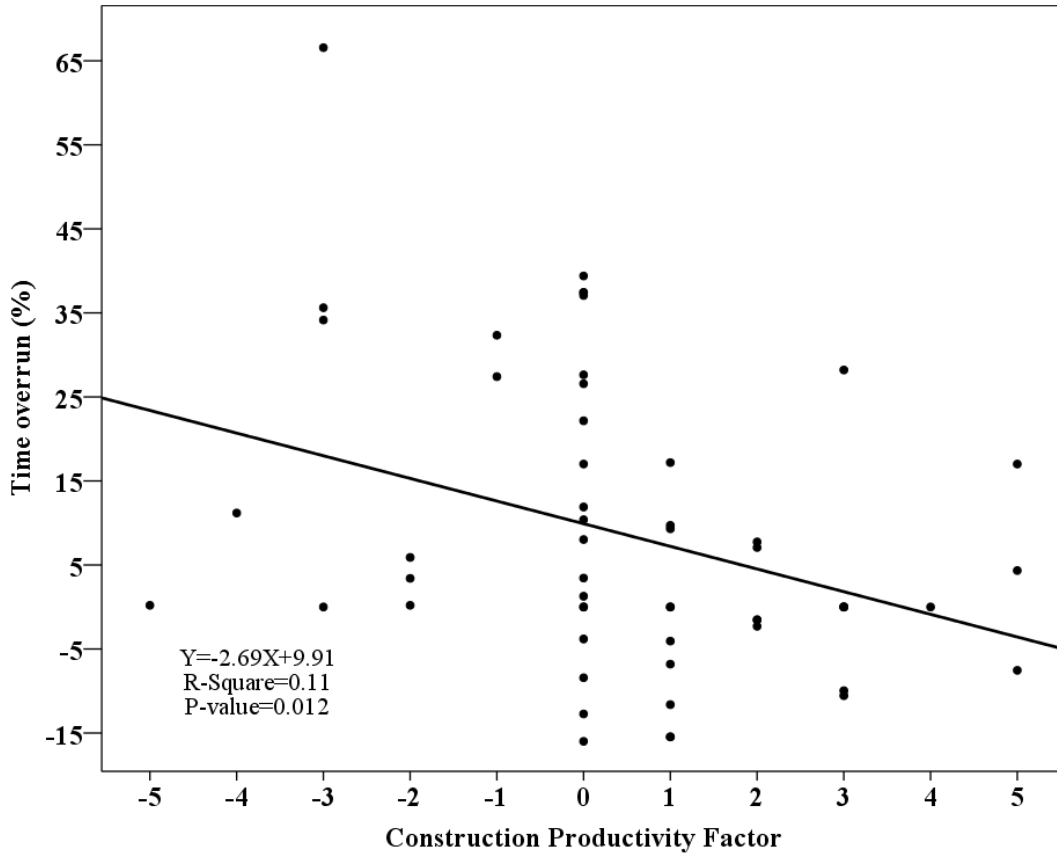
Fig. 3.7. Regression analysis of the Construction Productivity Factor and Time Overrun

(CII BM&M database)

3.5. Implications and Discussion of the Results

The initial implication of this study is to further support the assertion that a shortage of craft skills exists in some segments of the North American construction industry. Twenty-nine percent of (20 out of 68) the projects in the BM&M databases reported they experienced some level of shortage (availability of skilled labor score <0). While this number may seem low, it is important to note that 82% of these projects (56 projects) were executed within the Great Recession (2008-2010) when labor supply was more readily available. Among the RT-318 survey projects, this proportion reached 52% (15 out of 29), representing respondents that claimed their projects were impacted by craft labor shortage.

It should be noted that 90% (26 out of 29) of projects in this database started in 2012 in post- recession recovery era.

The result of a t-test on productivity performance in both datasets showed the significant difference in productivity between projects that experienced skilled labor shortage and those that did not. This substantial influence can be observed when the results in both tests show that the shortage in skills diminished the overall project productivity to less than what was expected in planning stages of projects (Projects reported shortage: RT-318: PF_{Mean}= 0.84<1, BM&M: P_{Mean}=-1.05<0) while, no craft recruiting difficulty resulted in project productivity higher than estimated during the project planning stages. (Projects reported no shortage: RT-318: PF_{Mean}= 1.03>1 & BM&M: P_{Mean}=0.89>0).

Further exploration by means of regression analysis showed that there was a significant correlation between higher craft recruiting difficulty and lower project productivity in both datasets.

This decline in productivity contributed to project schedule overrun. The result in a t-test for both databases demonstrated the statistically significant difference between average time overrun of projects that reported skilled labor shortage and projects that did not experience a shortage. Furthermore, regression analysis on two datasets supported and validated the result of prior tests demonstrating the statistically significant correlation between higher craft recruiting difficulty and higher time overrun.

Past studies on productivity (Dai et al., 2009; Roja and Aramvareekul, 2003; Liberda et al., 2003; Chang et al., 2007; Lim and Alum 1995 and El-Gohary and Aziz, 2014) have shown that when a project encounters a craft shortage, a lack of skill, experience, and competency

is the main reason behind the decline in productivity. In this situation, project managers tend to compensate for expected delays due to an expected decline in productivity by accelerating the project schedule using overtime. This has been argued by Hanna et al. (2005) and also validated by the analysis presented in this study as there is a statistically significant correlation between higher craft recruiting difficulty and higher percentage of overtime. However, additional decline in productivity is anticipated due to the using higher extended overtime (Lyneis and Ford, 2007; Hanna et al., 2005; Thomas and Raynar, 1997).

The analysis presented in this study cannot determine the relative contribution of these two influences, lack of skills and overtime, on project productivity, due to the lack of quantitative data available in the data sets. However, as the lack of skill and experience was identified as the main contributor to productivity decline in previous literature while the overtime impact was argued to significantly depends to the effectiveness of project management (Halligan et al., 1994, Thomas and Raynar, 1997), it can be reasonably assumed that the lack of skill, experience, and competency is a major contributor to the loss of productivity.

The regression models show a relatively weak, albeit statistically significant, correlation between time overrun and skilled labor availability, particularly among the CII BM&M projects (R^2=0.09). Considering many factors identified in past research as key contributors to project schedule performance make this low value not unexpected. However, the analysis presented here and past literature show that delay in project when encounter skill labor shortage usually is lessened with overtime. In this way, the major consequence of this mitigation strategy would be on the cost of a project, as overtime is associated with loss of productivity and also premium pay to the craft labor (for example, The average cost

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overrun in BM&M projects with a score of skilled labor availability less than zero is 5.8% comparing to -6.4% for project with a score equal or greater than zero). Nevertheless, in spite of the usage of extended overtime in CII BM&M projects, the analysis on this database and also on RT-318 projects showed that the influence of skilled labor shortage on time overrun remains substantial and cannot be eliminated completely, at least with this current traditional method of accelerating schedule.

3.5.1. Limitations of Study

The authors recognize the following limitations of the study:

1) The analysis was based heavily on industrial projects (90% of projects in RT-318 survey and 56% in CII BM&M database were industrial projects)

2) Although all models presented in this study were statistically significant, as they are simple linear regression models with a relatively low number of data points and also relatively low R2 value, they should be considered as informative rather than predictive models. However, low R^2 values are not surprising in analyzing construction data, given the large number of factors that have been identified in previous research that can impact construction project performance. The limitation of small sample size is not limited to this study and has been mentioned in previous research efforts in the area of construction management (Wanberg et al., 2013; Wong et al., 2008).

3.6. Conclusions and Recommendations

The main purpose of this research was to quantitatively examine the influence of skilled labor availability on construction project productivity and schedule performance. Data from 97 construction projects completed in the U.S. and Canada between 2001 and 2014

were collected from two data sources. A number of t-tests and linear regression analyses were conducted in both databases separately. The result of empirical analyses demonstrated the significant influence of craft labor shortage on construction project productivity and schedule performance. The analysis also showed that there are statistically significant associations between increased craft recruiting difficulty and lower project productivity and also increased schedule overrun.

The main contribution of this work to the body of knowledge is to fill the gap in existing literature by quantitatively modelling and elucidating the influence of craft labor availability on construction project productivity and schedule performance. This study supports and validates the previous qualitative studies that used opinion-based data to anecdotally link the shortage of craft labor to a project's lower productivity and delay. The strength of this study lies in the fact that the analysis on two different databases, with difference measures of craft labor availability and productivity shows similar results. This affirms the reliability and consistency of the results as they externally validate each other.

Although the presented models in this study are informative rather than predictive (due to relatively low R-squared values), they provide valuable insight for project management teams to perceive the risk of lack of skills on productivity and overall time performance of a project at planning stage. For instance, the model presented in Fig.2 shows the significant association between skilled labor availability and overall project productivity performance. Given various productivity measurements and the different trades involved in a project, the model built with subjective measurement — which is based on judgment from experienced project managers —provides a proper picture of the overall influence that skills shortage has on project productivity. Similar lessons also can be learned from schedule models as

they illustrate the similar patterns. Overall, these suggest the importance of preparing specific mitigation strategies with regard to the risk that craft labor recruiting difficulty poses on project productivity and schedule performance.

The North American construction craft labor segment is experiencing structural changes, including a workforce that is aging faster than all other private industries, national shortages in key industrial trades (e.g. welders, pipefitters, and electricians), and shrinking real wage gaps between construction craft labor and all other private industries (Taylor et al, 2016). These challenges present significant changes to the construction industry as they will increase the problem of craft labor availability. This underlying problem cannot be expected to improve unless these challenges are addressed not only within the construction industry but also in K-12 education and societal perceptions towards construction. However, understanding the level of impact that craft shortages are having through robust statistical analyses as presented here, will hopefully serve as a first step in developing the motivation for industry leaders, communities, and construction stakeholders to address this challenge.

CHAPTER 4: Modeling and Forecasting the Impact of Craft Labor Availability on Construction Project Cost Performance (Paper No.3)

Synopsis: North American construction industry began to experience a shortage of skilled labor since 1980s which continued as a repetitive cyclic trend over the past three decades. While this issue has received significant attention from researchers, less attention has been given to quantifying the impact of craft labor availability on construction project cost performance. The primary contribution of this study to the body of knowledge is to fill the gap in existing literature by quantitatively modelling and elucidating the influence of craft labor availability on construction project cost performance. Data from 97 construction projects completed in the U.S. and Canada were collected from two industry databases. The primary analysis shows that projects that experienced craft shortages underwent significant higher growth in cost overrun compared to projects that did not. Further analysis on two databases returned two robust multiple regression models that demonstrate similar pattern of the risk that craft labor shortage poses on project cost performance. Utilizing data combining techniques, two datasets were combined to obtain the best possible model from available data. While the final model is intended to be used by project management teams as a risk forecasting tool of craft labor variability on cost performance in a project context, it also can serve as a primary step in developing motivation for industry leaders, communities and construction stakeholders to address the challenge of skilled labor shortage in construction industry.

4.1. Introduction and Background

Construction is a labor-intensive industry and labor costs comprise a significant portion (30-50%) of a total actual cost of a project (McTague and Jergeas, 2002; Hanna et al., 2001). It is well known that labor cost is the most controllable part of a project as the cost of materials and equipment are significantly impacted by market price and are typically beyond the control of project manager. Considering the 2-3% of the total project cost as the profit margin of a contractor, hence, management of labor cost and productivity is critical to the financial success of a construction project (Hanna et al., 2005; Ernzen and Schexnayder, 2000).

North American construction industry began to experience a shortage of skilled labor since 1980s which continued on repetitive cyclic trend over the past three decades. The inevitable consequence of this shortage is difficulty in recruiting and maintaining skilled labor in projects which put their financial success in a precarious position.

The evidences of this shortage between 1980s and 2008 Great Recession has been discussed frequently in the past literature (Business Roundtable, 1983; Construction Industry Institute (CII), 1990; Business Roundtable, 1997; Chini, 1999; CURT, 2001; Rosenbaum, 2001; Goodrum, 2004; Sawyer and Rubin, 2007). The construction work slowdowns in 2008 Great Recession in the U.S. began temporarily amelioration the craft shortage for a period of time; however, the post-recession rapid economic recovery again initiated craft shortage. CII (2015) revealed that the severe shortage appeared particularly in the U.S. Southeast and Southwest regions among key craft trades including welder, pipefitter, and electricians. Taylor et al. (2016) conducted a survey among North American

construction companies and revealed that 52% of surveyed projects were impacted by skilled labor shortage. The surveyed projects in this study were completed during the recovery era between 2011 and 2014. The U.S. Bureau of Labor Statistics (2015) predicted that the construction industry adds 790,400 jobs by 2024. This development accounts for an average 1.2% annual rate of growth in employment, which is the second highest rate of growth among major industry sectors.

Project encountering craft labor shortage endure difficulties in recruiting and retaining a required level of skills and/or quantity of craft labors. When a required quality level of skills cannot be met, a project will be executed with less skilled workers. When craft labor quantity issue arises, a project cannot even meet its basic labor demand. A project executed on either of these two conditions is highly likely to experience a cost escalation. The past literature provides a wealth of information on how the shortage of skills can affect project cost performance. To propose testable hypotheses and risk model built on past researches' findings, the authors reviewed and examined the body of literature that discusses the impact of craft labor availability on construction projects cost performance as described in the next section.

4.2. The Impact of Skilled Labor Availability on Cost performance: Evidence from Previous Researches

Over the last two decades, there have been numerous researches about predicting accuracy of construction project actual cost. Of these studies, many attempted to investigate on the generic causes of cost performance in design and construction stage of projects. Doloi (2013) summarized the highlighted key factors in past researches into seven groups which

are project related factors (scope, lactation, size and type of project, etc.), contract related factors (contract management, form of procurement, etc.), project management factors (capability of construction team), quality related factors (inspection and testing of completed work, method and techniques of construction, etc.), planning related factors (effective monitoring and feedback process, construction control, etc.), market related factors (availability of labors, shortage of material, price fluctuation, etc.), and contractor related factors (contractor experience, communication between client and contractor, labor productivity, etc.). Doloi also conducted survey on 160 Australian construction client, consultant and contractor. The "lower labor productivity" and "availability and supplies of labor and material" were ranked among the top 30 factors (total of 48 factors) contributing to the construction cost performance. Akintoye (2000) conducted comparative study on 84 UK contractors range from very small to large firms about factors influencing contractor cost estimating practices. Overall, "availability and supply of labor and material" was ranked 10th among 24 identified factors. In addition, performing factor analysis, this variable also recognized as one of the significant contributors of the project cost performance.

Gharaibeh (2014) conducted Delphi study on project management teams of two power transmission mega projects in Canada. "Lack of contingency and escalation for material and craft labor costs in the initial estimate" was identified as one of the top 10 most important problem in managing project cost. In addition, "applying quantity-tracking concept to monitor changes of material and craft labor quantities" was mentioned as one of the top 10 most important lessons learned in managing a project cost performance.

In a quantitative analysis and in an attempt to establish a model for early cost estimation, Trost and Oberlender (2003) performed a factor analysis and multivariate regression on 45 identified cost drivers on 67 completed construction projects across the world. "Bidding and Labor Climate" factor is found as one of the five variables that significantly impact cost estimate accuracy, accounting for 14.5% of the prediction in the model. This factor includes the impact of bidding climate, labor productivity, contract type, project schedule, and logistic for engineering and construction. RSMeans (2016) suggests the cost allowance of 10% of the total construction cost for Building projects encountering the shortage of skilled labor. This allowance rises to the 11% for Heavy Industrial projects.

The mechanism of the impact of skilled labor availability on project cost is complex and can be through direct and indirect way and on interrelated processes. For instance, the cost escalation can be due to the increase in total craftwork hours due to the loss of labor productivity because of skills shortage. As an indirect way, a lack of experienced/skilled craft labor can result in further safety incidents occurrence (Karimi et al, 2016) which results in an additional direct cost (ex: clean up and repair, equipment damage) and indirect cost (ex: disrupted schedules) to a project (Improving Construction Safety Performance, 1982). In summary, loss of productivity, increase in extended overtime, increase in hourly wage, escalation in safety incidents, increase in amount of rework, and escalation of schedule overrun are major interrelated processes that ultimately result in further cost overrun in a project encountering skilled labor shortage.

4.2.1. The Impact through Loss of Productivity

Construction project productivity can be adversely affected by a shortage of skilled labor. The evidences of this significant impact have been discussed in numerous qualitative

opinion-based studies (Dai et al., 2009; Roja and Aramvareekul, 2003; El-Gohary and Aziz, 2014; Halligan et al. 1994; Liberda et al., 2003; Horner et al., 1989; Jarkas and Bitar, 2012; Lim and Alum, 1995). There are also quantitative studies that examined this issue by collecting and analyzing empirical data. Chang et al. (2007) in an attempt to quantify the impact of schedule compression on labor productivity found that there is a statistically significant relationship between the two ratios of "actual number of manpower at peak/estimated one" and "actual average manpower/estimated one" and the loss of productivity in projects. These two variables can be interpreted as an indication of shortage in skilled labor in a project. Heravi and Eslamdoost (2015) attempt to establish a predictive model for measuring and estimating construction labor productivity using artificial neural networks. They found by improving "labor competence", labor productivity could be increased by 13% to 18.7%, which make it as one of the top five influential factors that can make a high improvement in a labor productivity. Karimi et al. (2016) analyzed 97 construction projects completed in the US and Canada and found that there is a significant decline in productivity of projects experienced craft shortage compared to project did not. Conducting regression analysis, they also demonstrated that there is a significant association between increased skilled labor recruiting difficulty and decline in project productivity.

4.2.2. The Impact through the use of Overtime and Growth in Hourly Wage

Projects experiencing a shortage of skilled craft workers usually have a tight scheduling in order to meet a project deadline. Hanna et al. (2005) argued that overtime scheduling has become the prevalent option in this situation as it accelerates a project schedule and also an associated premium pay with overtime can attract the required workforce to complete

the project. In addition, Karimi et al. (2016) demonstrated that there is a significant association between increased craft recruiting difficulty and increased usage of overtime hour in construction projects. The extended overtime can significantly diminish a project productivity that ultimately result in growth of total craft workhours and final cost of a project. The evidences of an adverse impact of overtime on project productivity have been shown in past studies (Thomas, 1992; Halligan et al. ,1994; Thomas and Raynar, 1997; Lyneis and Ford, 2007; Hanna et al., 2005; El-Gohary and Aziz, 2014).

In addition to the loss of efficiency, this prevalent strategy usually is associated with premium pay which along with other approaches such as bonuses, loyalty rewards and promotions are common short-term solutions that project managers utilize for attracting and retaining workforce (Chini, 1999; Hanna et al., 2005). Therefore, the shortage of skilled labor often encompasses increase in craft labor's hourly wage. CII (2015) reported that trades with the highest level of shortage in the U.S. also had the highest actual wage growth compared to planned one in recent completed projects. The top three trades were pipe welders, pipefitters, and structural welders with the average actual wage growth of 6.0%, 5.4%, and 3.1% respectively.

4.2.3. The Impact through safety incidents occurrence

As mentioned before, a tight scheduling and scheduled overtime are the common circumstances of a project executing with a shortage of skilled labor. Ahmed et al. (1999) identified a tight construction schedule as the most serious factor affecting construction site safety. Overtime duties also can cause physical fatigue on craft workers (Lyneis and Ford, 2007), which can seriously affect implementation of construction site safety (Cheng et al., 2004). Furthermore, the consequence of tight scheduling is the higher work pressure

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on craft workers. The evidences of the influence of perceived work pressure by workers on unsafe work behavior have been discussed by several researchers. They claimed that workers tend to take safety shortcuts when they feel they are under pressure during the work (Choudhry and Fang, 2008; Brown et al., 2000).

Less experienced workers are more prone to safety incidents due to the lack of familiarity with proper construction procedures and processes. Choudhry and Fang (2008) found that experience has a significant role in unsafe behavior of craft workers. Glazner et al. (2005) found that factors such as inappropriate acts, inexperience, and deviations from safety instructions were the most common reasons for injuries, contributing to 54.4% of all observed injuries in their study.

Karimi et al, (2016) analyzed the influence of skilled labor shortages on project safety performance and demonstrated that there is a significant different in average Total Recordable Incident Rate (TRIR) of projects that impacted by craft labor shortage comparing to those did not. In addition, they demonstrate that there is a strong exponential association between increased skilled labor recruiting difficulty and increased TRIR.

The impact of construction injuries on project cost performance considering the direct and indirect cost of injuries is substantial. Hinze and Appelgate (1991) demonstrate that indirect cost which is substantially greater than the direct cost makes even the cost of minor injury considerable. The indirect costs are but not limited to Loss of productivity, Disrupted schedules, Administrative time for investigations and reports, Training of replacement personnel, Wages paid to the injured worker (s) and other workers for time not worked, Clean up and repair, Adverse publicity, Third-party liability claims against the owner, and Equipment damage (Improving Construction Safety Performance, 1982). Everett and

Frank (1996) found injuries accounts for 7.9% -15% of the cost of non-residential, new construction projects. This indicates the significant contribution of safety accidents to the cost overturn particularly when project experiencing craft labor shortage.

4.2.4. The Impact through schedule overrun

Shortage of skilled labor is one of the key contributors to the schedule overrun in construction projects. The significance of this influence has been argued by several scholars mainly in opinion-based studies (Baldwin and Manthei, 1971; Arditi et al., 1985; Wambeke et al., 2011; Abdul-Rahmaan et al., 2006; Toor and Ogunlana, 2008; Kaming et al., 1997; Assaf et al., 2006; Mahamid et al., 2012; El-Razek et al.,2008; Lo et al., 2006). Inadequate supply of labor, shortage of skilled workers, and low productivity of labor and supervisors have been recognized as three labor-related factors contributing to schedule overruns in projects.

Karimi et al (2016) presents a series of quantitative analysis on a total of 97 construction project completed in the US and Canada and demonstrates that there is a significant difference between average time overrun of projects experienced craft shortage and projects did not. The study also shows that there is a statistically significant association between craft recruiting difficulties and time overrun in construction projects.

Delay in a project adds direct and indirect cost. The direct cost is the cost associated with additional labor, equipment, and material to complete the job and the indirect cost is but not limited to site and home office overhead (Chester and Hendrickson, 2005). The evidences of the impact of project duration variation on cost performance has been discussed frequently in the past literature. Akintoye (2000) attempt to identify the factors

influencing project cost estimating practice. Conducting factor analysis, it was revealed that the extent of variation in a project duration is one of the seven influencing factors contributing to the project cost performance. Flyvbjerg et al. (2004) investigated on the causes of cost escalation in 258 transportation infrastructure projects in 20 nations. It was demonstrated that cost escalation is highly dependent on the length of project-implementation phase. The implementation phase was defined as the period from the decision to build to construction is completed and operations have begun. Flyvbjerg et al. (2004) concluded that in order to manage the cost escalation in a project more effectively, it is essential for project management team to minimize the risk of delays in a project. Developing a cost escalation model, Touran and Lopez (2006) demonstrated that project delay has substantial impact on the magnitude of cost overrun in large long-term project.

4.2.5. The Impact through Quality Performance

Shortage of skills in a project can cause construction field rework. Construction Owners Association of Alberta (COAA) (2002) developed fishbone rework cause classification system, which consists of five main areas with four causes in each area. Human Resource Capability is one of the main area in which three of four causes are related to the craft labor availability namely "insufficient skill levels", "inadequate supervision & job planning", and "excessive overtime". Based on COAA rework cause classification system, Fayek et al., (2003) attempted to quantify the cost of each cause of rework in a mining expansion venture project. The root cause analysis on 125 field rework incidents performed which account for 0.87% of the total cost of construction phase. Conducting third level cause analysis for "inadequate supervision & job planning" causes showed that inadequate technical knowledge, lack of training and experience, and inadequate

supervisor/foreman/tradesmen ratios contribute to the 6.87% of the total cost of rework. Regarding "insufficient skill levels" causes, lack of adherence to procedure and shortage of skilled labor and supervision account for 6.25% of the total rework cost. Overall, two causes in the area of human resource capability, insufficient skill levels and inadequate supervision and job plan, account for 13.12% of the total construction field rework cost.

With much research effort on the impact of rework on cost of project over the last two decades, it is now well known that rework in one of the key contributors to the project's cost overrun. Researchers found rework could account for 2.4% to 12.4% of a total cost of a project (Burati et al., 1992; Hwang et al., 2009; Love and Li, 2000; Josephson and Hammrlund, 1999).

4.2.6. Point of Departure

The body of literature provides strong qualitative support for the significant contribution of craft labor availability to project cost performance. In addition, this contribution has been demonstrated quantitatively through the impact on productivity, safety, scheduled overtime and overall schedule performance. However, no studies have yet examined an empirical overall impact of craft labor shortage on project cost performance. This study attempts to fill this knowledge gap by collecting and analyzing the empirical data of projects recently completed in the US and Canada to quantitatively modelling and elucidating the influence of craft labor availability on construction project cost overrun. In addition, the remaining influential processes not proved quantitatively in past studies will be examined. These processes include impact of craft shortage through change in hourly wage, quality performance and also through impact of time overrun on cost overrun.

To accomplish these aims, the following research objectives were defined: 1) to examine whether there is a significant association between craft staffing difficulty and hourly wage increase and quality performance decrease. In addition, to examine if there is a significant influence of time overrun on cost overrun. 2) to identify whether there is a significant difference in cost overrun of projects that experienced a craft labor shortage versus those did not; 3) to identify whether there is a significant relationship between craft labor staffing difficulty and actual cost growth; and 4) to develop a model that quantifiably link craft labor variability to project actual cost overrun.

4.3. Research Methods

4.3.1. Data collection

The data used in this research were obtained from two different sources to enhance the validity and reliability of the study. The first source was a primary data collection effort through a Construction Industry Institute (CII) Research Team number 318 (RT-318) survey. This survey collected project performance and workforce demographic data on completed construction projects in the U.S. and Canada. The survey was developed; pilot tested and distributed to the CII and non-CII member construction organizations. There were 29 total responses to the survey, with 26 projects from the U.S. and three from Canada. The average construction experience of the respondents was 24.79 years, which indicates the reliability of collected data particularly on the subjective data of craft labor availability. The majority of survey responses involved heavy industrial projects (25 out of 29) while the remaining projects were building (one project), Light Industrial (one project), and Infrastructure (two projects). Seventeen projects used open shop (59%), seven used

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union labor (24%) and five used both options (17%) to staff their craft workforce. The projects were distributed across the North America covering 18 States in the US and three Canadian provinces. With exception of two projects that performed between 2009 and 2011, all other 27 projects were performed and completed between 2011 and 2014. The results of this survey were used to construct a database of project characteristics. Additional detail on the survey effort is described in Taylor et al. (2016).

The second data source was obtained through the CII Benchmarking and Metrics (CII BM&M) database. The CII BM&M database was designed to capture comprehensive data of construction projects performed by CII member companies. For the purpose of this research, the projects in this database that reported data related to the availability of craft workers were selected. This subset consisted of 68 completed projects of which 59 were performed in the U.S. and nine in Canada. Out of these 68 projects, 31 projects (45%) were heavy industrial, 24 projects (35%) were commercial building, seven projects (10%) were light industrial and six projects (9%) were infrastructure projects. All projects in this database were executed between 2001 and 2013 (75% of projects between 2001-2011, and 25% between 2012-2013). Table 1 shows the average, median, and range of the size of projects in terms of actual cost, actual time, and actual craft direct work hours in both databases.

Table 4.1. Summary of projects size in RT-318 Survey and CII BM&M Database

Database	Project Size	Average (Median)	Min, Max
RT-318 Survey (29 projects)	Actual Cost ($M)	455.2 (45)	3.6, 8549
	Actual Schedule (Day)	554.7 (533)	134, 1648
	Craft Work Hour (1000 hr.)	610.6 (321)	13.3, 3777.9
CII BM&M (68 projects)	Actual Cost ($M)	142.5 (40.1)	0.5, 1799.3
	Actual Schedule (Day)	1054.5 (678)	46, 3131
	Craft Work Hour (1000 hr.)	732.5 (110)	2.5, 8870.6

4.3.2. Skilled Labor Availability Measurement

In both databases, an estimate of the level of craft shortage in projects relied on subjective evaluations of the project management team. The major benefit of this procedure was to compensate for the deficiency in the quantitative data for different trades in the RT-318 projects and the absence of quantitative data for different trades in the BM&M projects.

In the RT-318 survey, the respondents were asked to indicate whether their project was impacted by a craft labor shortage. Furthermore, they were asked to indicate the level of craft staffing difficulty they experienced on their project for 13 craft labor trades, which included carpenter, pipefitter, electrician, boilermaker, sheet metal, ironworker, pipe welder, structural welder, equipment operator, crane operator, millwright, instrument fitter, and supervisors. There were five levels of staffing difficulty defined in the survey ranging from No Difficulty to Very Severe (Table 2).

Table 4.2. Levels of craft staffing difficulties in the RT-318 survey

Level	Definition	Score
No difficulty	There was no shortage. Able to staff the project with no delay on construction	0
Slight	Recruiting difficulties led to consumption of schedule float and/or contingency	1
Moderate	Recruiting difficulties led to delay of completing project activities on time	2
Severe	Recruiting difficulties led to delay of completing project milestones	3
Very Severe	Recruiting difficulties led to project delay	4

To provide an overall level of craft staffing difficulty for each project, the authors calculated an aggregate average of craft staffing difficulty across these 13 trades for each project as follows:

$$\text{Craft recruiting difficulty score of a project} = \frac{(0 \times A) + (1 \times B) + (2 \times C) + (3 \times D) + (4 \times E)}{13}$$

Eqn. (1)

in which A, B, C, D, and E are the number of trades in each level of staffing difficulty from No difficulty to Very severe.

In the CII BM&M database, the respondents indicated the level of availability of skilled labor across all trades compared to what had been specified during the planning stage of their project. These levels ranged from Extremely Negative (-5) to Extremely Positive (+5), and Zero represents an "As Planned" situation.

4.3.3. Cost Performance

The cost performance in both databases was measured by the percentage of cost overrun relative to the planned construction cost (Equation. 2):

$$\text{Cost Overrun (\%)} = \frac{\text{Actual Cost} - \text{Budgeted Cost}}{\text{Budgeted Cost}} \times 100$$

Eqn. (2)

4.3.4. Schedule Performance

The schedule performance in both databases was measured by the percentage of schedule overrun relative to the planned construction schedule (Equation. 3):

$$\text{Schedule Overrun (\%)} = \frac{\text{Actual Schedule} - \text{Planned Schedule}}{\text{Planned Schedule}} \times 100$$

Eqn. (3)

4.3.5. Quality Performance

In the absence of quantitative data of amount of rework in both databases, the quality performance in CII BM&M projects was measured by subjective evaluation of project management team. The respondents of the CII BM&M questionnaire were asked to indicate the level of success of their project's quality performance on the scale of 1 as "not at all successful" to 7 as "extremely successful".

4.3.6. Hourly Wage Increase

The RT-318 survey asked respondents to provide an estimated and actual raw hourly wage of each aforementioned 13 trades in their projects. Therefore, an hourly wage increase in a

project was measured by the percentage of change in wage relative to the estimated one (Equation. 4). It should be noted that CII BM&M database has no data related to hourly wage in projects.

$$\text{Hourly Wage Increase (\%)} = \frac{\text{Actual hourly wages} - \text{Estimated hourly wages}}{\text{Estimated hourly wages}} \times 100$$

Eqn. (4)

Cost overrun like other project performance parameters (i.e. schedule overrun, hourly wage increase) has several intervening variables such as changes in scope, change order, weather, etc. In order to take into consideration of these intervening variables in analysis, two most valid statistical analysis methods, t-test and regression, were used for data analysis.

4.4. Data Analysis

4.4.1. Primary Hypothesis Development

The purpose of primary hypothesis development is to examine the influential processes of the impact of craft shortage on cost performance that have not yet examined quantitatively it the past literature. These processes include impact of craft labor availability on quality performance and hourly wage increase and also impact of time overrun on cost overrun.

Simple linear regression analysis was selected to examine the hypothesis. The null hypothesis for each analysis was that no relationship existed between two variables. The alternative hypothesis was that there is a relationship between the two variables, which was determined by obtaining the p-value of less than 0.05. For all regression analyses, outliers have been detected and removed from the analysis using the Cook's distance, as suggested by Agresti (2015). The two main variables used in the regression analyses to assess the

level of craft labor availability were the craft staffing difficulty variable (RT-318 survey) and the skilled labor availability variable (CII BM&M). Both of these two variables are categorical with natural ordering; hence they can be referred to as ordinal variables. In order to use more powerful methods available for quantitative variables such as regression, it is possible to assign numerical scores to categories of ordinal variables and treat them as an interval variable (Agresti and Finlay, 2009). Both of these variables were assigned numerical scores and were suitable to be used in regression analysis. It should be noted that "meeting quality expectation" variable in BM&M database also has a similar status as skilled labor availability variables. All hypotheses are described in detail in Table 3.

Table 4.3. Summary of Primary Hypothesis Development

Hypothesis	Dataset	Dependent variable	Independent variable	Null Hypothesis	Alternative Hypothesis
H1	RT-318 Survey	Hourly Wage Increase	Craft Staffing Difficulty	There is no relationship between variables	There is a relationship between Hourly Wage Increase and Craft Staffing Difficulty
H2	RT-318 Survey	Cost Overrun	Time Overrun	There is no relationship between variables	There is a relationship between Cost Overrun and Time Overrun
H3	CII BM&M	Cost Overrun	Time Overrun	There is no relationship between variables	There is a relationship between Cost Overrun and Time Overrun
H4	CII BM&M	Meeting Quality Performance Expectation	Skilled Labor Availability	There is no relationship between variables	There is a relationship between Meeting Quality Performance Expectation and Skilled Labor Availability

The regression analysis for hypothesis (H1) shows that there is a significant association between increased craft staffing difficulty and increased hourly wage in construction projects. The p-value of less than <0.0001 resulted in rejection of the null hypothesis and acceptance of the alternative hypothesis. The analysis also shows that impact of time overrun –which could be due to the shortage of skilled labor- on cost overrun is considerable. The p-values of hypotheses H2 and H3 were 0.0004 and 0.0065 which indicate the significance of both relationships. The last analysis examines the influence of skilled labor availability on quality performance. The p-value of the model was 0.0076 which lets us to conclude that there is significant association between these two variables. Table 4 shows the detailed result of all hypothesis testing.

Table 4.4. Summary of the Result of Primary Hypothesis Testing

Model	Number of data points	Equation	R^2	P-value
H1	96	Y = –1.03 + 1.83X	0.24	<0.0001
H2	20	Y = 1.99 + 0.46X	0.51	0.0004
H3	52	Y = -7.4 + 0.35X	0.14	0.0065
H4	55	Y = 5.86 + 0.16X	0.13	0.0076

The analyses of hypothesis testing along with other quantitative studies cited before explicate the various processes that project cost can be increased due to the shortage of skilled labor. The next analysis explores the overall influence of craft labor shortage on project cost performance.

4.4.2. Main Hypothesis Development

The respondents of the RT-318 survey were asked whether their projects were impacted by a craft labor shortage. Therefore, the projects in this database can be divided into two groups of: 1) project impacted by craft labor shortage and 2) projects not impacted by a craft labor shortage. The projects in the CII BM&M also were divided into two groups: 1) projects with a skilled labor availability score of less than zero (score<0), which are classified as projects that experienced some level of skilled staffing difficulty; and 2) projects with a score of equal or greater than zero (score≥0), which are classified as projects that did not experience skilled labor staffing difficulty. The CII BM&M questionnaire defined the zero score as a situation where actual skilled labor availability was similar to what was expected during project planning (i.e. skilled labor availability did not positively or negatively impact project performance when compared with the project plan) and scores greater than zero as the condition where the availability of craft workers had a positive impact on project performance. Therefore, it can be reasonably assumed that when a project in this database has a score of equal or greater than zero, the project experienced no craft staffing difficulty while projects with scores between -1 to -5 experienced some level of skilled labor shortage. As shown in Table 5, to determine the significance of the impact of craft labor shortage on project cost performance, two following hypotheses were developed.

Table 4.5. Summary of Main Hypothesis Development

Projects Classification	Database	Null Hypothesis	Alternative Hypothesis
H5: projects impacted by craft shortage vs. not impacted	RT-318 Survey	There is no difference in mean cost overrun.	The mean cost overrun is higher in projects impacted by craft shortage.
H6: projects with availability of skilled labor score <0 vs. score≥ 0	CII BM&M	There is no difference in cost overrun.	The mean cost overrun is higher in projects with score <0.

A t-test was conducted to determine if the difference in average cost overrun between the two groups of projects in each database were statistically significant. Shapiro–Wilk statistics were examined to test the normality assumption of each group. If the Shapiro–Wilk statistics is not significant, the null hypothesis, which asserts the normal distribution of data points, cannot be rejected. The result indicated that probability values of the test for both H5 and H6 were greater than 0.05, which means the normality assumption of the t-test was satisfied for both hypotheses. The Levene's test was performed to examine the assumption of equality of variance. The results of the test show that this assumption was also satisfied, as they were not significant at the 0.05 level for both hypotheses. As shown in Table 6, the average cost overrun in the RT-318 survey projects that were impacted by a craft labor shortage was 15.47% compared to 0.73% for projects not impacted by a craft labor shortage. This difference is significant at 0.1 level. In the CII BM&M projects, the average cost overrun in projects with a craft availability score of less than zero was 2.3% while the average for projects that experienced no skilled labor shortage was -8.3%. The p-value of the test was 0.004 which resulted in rejection of the null hypothesis (H6), and allowed us to conclude that cost performance in these set of projects is substantially impacted by shortage of skilled labor.

Table 4.6. Hypothesis testing result of cost overrun comparison

Hypothesis	Projects impacted by craft shortage			Projects not impacted by craft shortage			Levene's	T	Df	P
	Mean	N	W	Mean	N	W	F			
H5	15.47	10	0.87*	0.73	11	0.95*	0.036*	1.56	19	0.067
H6	2.3	18	0.97*	-8.3	45	0.96*	0.024*	2.72	61	0.004

W: Shapiro–Wilk Statistics

* = Not Significant at 0.05 level

The analyses of hypothesis testing demonstrate the substantial influence of skilled labor staffing difficulty on project cost performance. The results justify a deeper exploration on these influential relationships in construction projects.

4.4.3. Statistical Model Development

Multiple linear regression analysis was performed to determine the quantitative relationship between craft labor staffing difficulty and project cost overrun. Two predictor variables were actual construction cost and craft staffing difficulty score. Wong et al. (2008) in developing a predictive labor demand model for construction project found that construction cost is the most significant determinant of labor demand. Although the craft staffing difficulty variable inherently includes both demand and supply of craft labor in a project, it is reasonable to forecast its influence on cost overrun with consideration of actual cost of a project. It is expected that labor shortage in a larger project results in higher cost overrun as execution of a project relies on more number of craft workers.

Diagnostic tests were performed to examine the reliability of the models. Multicollinearity was tested by variance inflation value of each variable. Heteroscedasticity problem were

examined by a residual analysis. The Anderson-Darling statistics were examined for the normality assumption of the models. In addition, outliers have been detected and removed from the analysis using the Standard residual and Cook's distance, as suggested by Agresti (2015).

4.4.4. Data combining

Since there are two data sources available in this study and hence two statistical models can be derived from data analysis, the authors decided to combine two data sources to take the most advantage of available data. Generally, the main reason behind the data combining is the use of multiple data source to construct a more accurate and reliable model when each type of data has a different level of precision and systematic bias (Shyr, 1993).

The combining data– which are entitled transferability and updating model in the past literature – is based on the idea that estimated model from previous study may provide useful information for estimation of parameters of the same new model even if the true values of the parameters are not expected to be equal (Ben-Akiva and Bolduc, 1987).

The methods of data combining are frequently used in past literature to transfer model parameters and/or travel data from one geographic region to another (Morikawa, 1989; Zhang and Mohammadian, 2008; Karasmaa, 2007; Ben-Akiva and Bolduc, 1987). The other examples are combining laboratory and field data in rail fatigue analysis (Shyr, 1993) and spatially transferring automobile Co_2 emission model between two cities (Siuhi et al. 2012). Data combining techniques also can be used for temporal transferability. For instance, Badoe and Miller (1995) combined two datasets of different temporal contexts

(year 1964 & 1986) of a fixed geographic area (Toronto, Ontario, Canada) to improve the model prediction of work trip mode choice in 1986.

In this study, the database of BM&M projects that executed in earlier period of time (2001-2013, 75% executed between 2001-2011) will be combined with more recently performed projects of RT-318 survey (2011-2014) to build a more reliable risk forecasting model suitable for current era. The common combining data procedures used in past literature are Joint Context Estimation, Bayesian Updating Method, and Combined Transfer Estimator (CTE). Each technique has its own theoretical background, strengths and limitations which make them uniquely suitable for different situations.

4.4.4.1. Joint Context Estimation

This method combines two databases and use them simultaneously in determining the parameters of new model. The basic theory of the method is discussed by Bradly and Daly (1991) and Ben -Akiva and Morikawa (1990). The underlying idea of this method is to adjust the random variation in the utility function of the different data sets to be equal (Karasmaa, 2007). In addition, this method can produce estimates of parameters that are not shared in both databases (Shyr,1993). Under the assumption of equality of parameter vector of models from two databases, the least square estimator of combined model is calculated as follows:

$$\beta = (X^T X) X^T Y$$

in which $Y = \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}$ is the vector of response variable form two databases and $X = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$ is the explanatory variables from two databases.

4.4.4.2. Bayesian Updating

Applying the classical Bayesian analysis and introduced by Atherton and Ben-Akiva (1976), this method estimates updated parameters of model with combining the parameter of model derived from two data sources. The underlying assumption of this method is that two models share the same parameters and new sample are used to re-estimate the distribution of the new model coefficients (Atherton and Ben-Akiva, 1976). The major advantage of this procedure is economic that is it permits the use of small sample survey to update the prior model while the sample were not statistically adequate to generate the model (Atherton and Ben-Akiva, 1976).

Based on normality assumption, the method is expressed mathematically as follows (Karasmaa, 2007):

$$\widehat{\boldsymbol{\beta}_{BU}} = \left(\Sigma_i^{-1} + \Sigma_j^{-1} \right)^{-1} \left(\Sigma_i^{-1}\widehat{\boldsymbol{\beta}_i} + \Sigma_j^{-1}\widehat{\boldsymbol{\beta}_J} \right)$$

Eqn. (5)

in which $\boldsymbol{\beta_{BU}}$ is the updated vector of parameters of the final model, $\boldsymbol{\beta_i}$ and $\boldsymbol{\beta_j}$ are the estimated vector of parameters of the first and second model and Σ_i and Σ_j are the covariance matrix of the first and second model. The covariance of final model can be calculated as $\left(\Sigma_i^{-1} + \Sigma_j^{-1} \right)^{-1}$.

4.4.4.3. Combined Transfer Estimator (CTE)

Combined Transfer Estimator method is a generalization of the Bayesian Updating Method as it explicitly takes into consideration of the bias transfer. If the transfer bias, which is defined as the difference between two parameters from two data sources, is not negligible,

the pooled and Bayesian Updating method is not appropriate and instead CTE Method should be used for data combining (Ben-Akiva and Bolduc, 1987). This procedure calculates the weighted average of models' parameters and assign the weight to each parameter in such a way that the mean square error (MSE) of the updated parameters is minimized (Ben-Akiva and Bolduc, 1987). The model can be expressed as follows (Karasmaa, 2007):

$$\widehat{\beta_{CTE}} = \left((\Sigma_i^{-1} + \Delta\Delta^T)^{-1} + \Sigma_j^{-1}\right)^{-1} + \left((\Sigma_i^{-1} + \Delta\Delta^T)^{-1}\widehat{\beta_i} + \Sigma_j^{-1}\widehat{\beta_j}\right)$$

Eqn. (6)

in which β_{CTE} is the updated vector parameter of the final model, β_i and β_j are the estimated parameters of first and second model and Σ_i and Σ_j are the covariance matrix of the first and second model. $\Delta = (\beta_i - \beta_j)$ is the transfer bias and Δ^T is the transpose of the matrix Δ. The covariance matrix of final model can be calculated as $\Sigma_{CTE} = \begin{pmatrix} \Sigma_i^2 & 0 \\ 0 & \Sigma_j^2 \end{pmatrix}^{-1}$.

4.4.5. Craft Staffing Difficulty Scale Conversion

To combine two models derived from two databases, it was necessary to have comparable models. Since the two databases had different scales to measure the craft worker availability, it was needed to convert one database's scale to another one and create a single measurement across all projects. The scale in RT-318 survey has no measure for condition of surplus of craft labor similar to CII BM&M scale (+1 to +5), therefore the only option is to convert the CII BM&M's scale to the RT-318's one. Any number between zero (As Planned) to +5 (Extremely Positive) in CII BM&M database was converted to No difficulty level (0) in the RT-318 survey. As discussed earlier, this conversion assumed that projects

with scores in this range were not impacted by a shortage of craft workers. However, there were only 17 projects among the total of 68 projects that has score more than zero. The scores between -5 (Extremely Negative) to -1 in the CII BM&M also were scaled proportionally to the number between 1 (Slight) to 4 (Very Severe), as defined in the RT-318 survey. This can be done by multiplying any score between -1 and -5 by -4/5. Fig. 1 illustrates the whole scale conversion process.
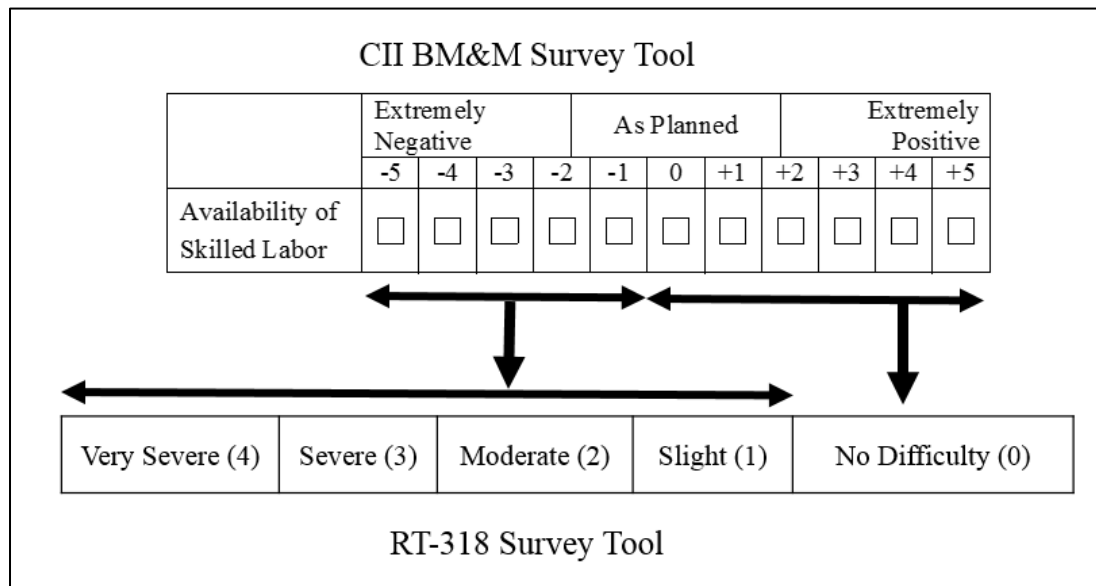
Figure 4.1. Process of converting the BM&M scale of availability of craft workers to RT-318 survey's scale

4.4.6. Model from CII BM&M Database

The total available data points for this analysis was 64. The analysis returned the regression model contains both two aforementioned variables. The p-value of the model was less than 0.0001, which indicates the adequacy of the model. The R^2 value of the model is 0.59 with an adjusted R^2 of 0.58. Table 7 shows the detail of statistical analysis of the model.

Table 4.7. Regression model of impact of craft staffing difficulty on construction cost overrun (CII BM&M Database)

No.	Dep. Variable	Const.	Actual Cost	Staffing Difficulty	F	P	R^2	Adj R^2	Jarque -Bera
64	Cost Overrun	-15.84*3	0.077*3	10.699*2	43.91	<.0001	0.59	0.58	0.74*

*3 = t-statistics significant at 0.0001 level; *2= t-statistics significant at 0.001 level;

*= Jarque-Bera statistics not significant at 0.05 level.

4.4.7. Model from RT-318 survey Database

The total available data points for this analysis was 17. The analysis again returned the regression model contains both two variables. The p-value of the model was 0.0019, which indicates the significance of the model. The R^2 value of the model is 0.59 with an adjusted R^2 of 0.53. Table 8 shows the detail of statistical analysis of the model.

Table 4.8. Regression model of impact of craft staffing difficulty on construction cost overrun (RT-318 survey Database)

No.	Dep. Variable	Const.	Actual Cost	Staffing Difficulty	F	P	R^2	Adj R^2	Jarque -Bera
17	Cost Overrun	-9.167*	0.0058*3	11.132*2	10.08	0.0019	0.59	0.53	0.159

* = t-statistics significant at 0.15 level; *2= t-statistics significant at 0.05 level;
*3= t-statistics significant at 0.01 level.

4.4.8. Model Transferability

Both models demonstrate similar pattern of the impact of skilled labor availability on project cost performance. However, the coefficient of actual cost variable is higher in model derived from CII BM&M database. As discussed earlier, the BM&M is set as a primary database and then will be updated with RT-318 survey data. To examine models and choose the best data combining methods for this study, all three transferred models were calculated (Table 9).

Table 4.9. Transferred models of the impact of craft staffing difficulty on construction cost overrun (BM&M data updated by RT-318 survey data)

Transferability Methods	Transferred Model
Joint Context Estimation	Construction Cost Overrun = -10.74 + 0.008×Actual Construction Cost + 15.04 × Craft Staffing Difficulty
Bayesian Updating Method	Construction Cost Overrun = -10.64 + 0.007×Actual Construction Cost + 14.62 × Craft Staffing Difficulty
Combined Transfer Estimator (CTE)	Construction Cost Overrun = -10.63 + 0.006×Actual Construction Cost + 11.06 × Craft Staffing Difficulty

4.4.9. Transferability Assessment and Model Selection

To assess prediction performance of the transferred models three measures were used. These measures have been used widely in past literature to examine transferability performance of transferred model (Koppelman and Wilmot, 1982; Karasmaa, 2007; Sikder et al, 2014).

Proposed by Koppelman and Wilmot (1982), the Transferability Test Statistics (TTS) is used to examines the difference between transferred model and application model (RT-318 model). The null hypothesis is that the coefficients of transferred model do not deviate significantly from application model (RT-318 model). If the TTS-value shown is equation 7 is greater than the critical chi-square value with degrees of freedom equal to model parameters, the null hypothesis will be rejected.

$$TTS = -2(L_j(\widehat{\beta}_i) - L_j(\widehat{\beta}_j))$$

Eqn. (7)

in which $L_j(\widehat{\beta}_i)$= log-likelihood for the transferred model applied in application data (RT-318 projects) and $L_j(\widehat{\beta}_j)$= log-likelihood of the application model (RT-318 model) based on the its data set.

The Transfer Index (TI) is used to measure the degree of goodness-of-fit of transferred model relative to the model estimated from application context (RT-318 model). TI is expressed mathematically as follows (Koppelman and Wilmot (1982):

$$TI = \frac{L_j(\widehat{\beta}_i) - L_j(\widehat{c}_j)}{L_j(\widehat{\beta}_j) - L_j(\widehat{c}_j)}$$

Eqn. (8)

in which $L_j(\widehat{\beta}_i)$ and $L_j(\widehat{\beta}_j)$ are as defined before and $L_j(\widehat{c}_j)$ is the log-likelihood of a reference model in application context (RT-318 model). The upper bound of TI is 1 and the closer the TI value to the 1, the more transferable is the model.

The last test is the Relative Aggregate Transfer Error (RATE) which measures the ratio of Root Mean Square Error (RMSE) value of a transferred model to the application model (RT-318 model). The RATE value is calculated as follows (Koppelman and Wilmot (1982):

$$RATE = \frac{RMSE_i\,(\boldsymbol{\beta_j})}{RMSE_i\,(\boldsymbol{\beta_i})}$$

Eqn. (9)

in which $RMSE_i\,(\beta_j)$ is the root mean square error of the transferred model on application context data set (RT-318 dataset) and $RMSE_i\,(\beta_i)$ is the root mean square error of the RT-318 model. The lower the value of RATE indicates the less aggregate error hence the higher prediction performance of transferred model. Table 10 shows the result of all three transferability tests.

Table 4.10. Model Transferability Assessment

Transfer Methods	TTS	TI	RATE
Joint Context Estimation	10.642*	0.298	1.263
Bayesian Updating	7.642*	0.496	1.194
Combined Transfer Estimator	0.948	0.938	1.129

* = chi-squared statistics significant at 0.05 level

As shown in Table 9, the TTS value for Joint Context Estimation and Bayesian Updating method is more than critical $\chi2$ -value (5.991) which suggest that these models cannot be fully substitute the best application context model. The TTS value is not statistically

significant for Combined Transfer Estimator (CTE) method which make this model desirable. The TI value for the CTE method is higher and close to the 1 which again shows the better performance of this transferability method compared to other two methods. the RATE value of CTE is lower among three methods which indicates this model has the least aggregate-level error and therefore higher predictive ability performance compared to other models. In summary, the CTE model demonstrates a superior performance comparing to other models in all transferability tests, therefore this model is selected as the desired risk model.

$$\textbf{Construction Cost Overrun} = \textbf{-10.63} + \textbf{0.0061}\times\textbf{Actual Construction Cost} +$$
$$\textbf{11.06}\times\textbf{Craft Staffing Difficulty}$$

Eqn. (10)

in which and with regards to the available data, Craft Staffing Difficulty variable range between 0 and 3.2, and Actual Construction Cost variable ranges is between \$M0.5 and 8549.

4.5. Discussion

Cost performance of a construction project is a complex function of many factors. As the model presented in this study is built by only two variables, it should be only used as a risk forecasting tool to assess the risk that craft labor shortage poses to cost performance. The primary benefit of this risk estimation is to make project management teams able to determine whether mitigation strategies are warranted to prevent potential shortfalls in project cost performance.

The strength of this risk forecasting model lies in the fact that two primary models derived from two databases with two different temporal contexts show almost similar pattern within the two robust regression models. This affirms the reliability and consistency of the results of analysis as they externally validate each other. To obtain the most benefit of having two datasets and to enhance the model transferability, two models were combined utilizing three major transfer methods. Then assessing forecasting ability with three major transferability tests, the best fit model was selected. It is expected that presented transferred model has superior performance in estimation of the risk in current era comparing to the two main models as it is based on relatively large number of projects (CII BM&M) which is updated with data of recently executed projects.

4.5.1. Limitations of study

Although the final model provides beneficial and statistically valid results, it is recognized that it is subject to the following limitations:

1. The analysis was based heavily on industrial projects (90% of projects in RT-318 survey and 56% in CII BM&M database were industrial projects)

2. Although both multiple regression models have reasonable R^2 value for prediction purpose, since they contain only two influential variables of cost performance, they can only be used as an informative risk forecasting tool instead of predictive tool.

4.6. Conclusions and recommendations

The main purpose of this research was to quantitatively modelling the influence of skilled labor availability on construction project cost performance. Data from 97 construction

projects completed in the U.S. and Canada between 2001 and 2014 were collected from two data sources. A primary hypothesis testing proved those processes of the impact of craft shortage on cost performance that have not yet examined quantitatively but have been argued by previous opinion-based studies. In addition, the main hypothesis testing affirmed that there is statistically significant difference in cost overrun of project experienced craft labor shortage. Further analysis by means of multiple regression analysis resulted in two robust models derived from two databases that show similar pattern of the risk of craft shortage on project cost performance. Finally, utilizing the common and valid approach of data combining, the final risk forecasting tool was obtained by combining two datasets.

The main contribution of this work to the body of knowledge is to fill the gap in existing literature by quantitatively modelling and elucidating the influence of craft labor availability on construction project cost performance. This study also supports and validates the previous qualitative studies that used opinion-based data to anecdotally link the shortage of craft labor to a project's cost growth.

Although the presented model is intended to be used as a risk forecasting tool in a construction project context, perhaps its broader and more important implication is on construction industry as one of the major U.S. industry sectors with second highest rate of growth over the next decade. Considering other quantitative studies cited earlier that shows the adverse impact of craft labor shortage on project schedule, productivity, and safety performance, and on the other hand, studies that discuss the recent structural change in the U.S. construction workforce, makes the risk alarming.

Taylor et al. (2016) shows that U.S. construction workforce is aging faster than all other private industries. They also argued that there is a significant shift in craft workers'

preferences from work satisfaction to higher income and job security while there is shrinking real wage gaps between construction craft labor and all other private industries. In addition, CII (2015) stated that there are national shortages in key industrial trades (e.g. welders, pipefitters and electricians). CII also revealed that high school graduation rates in Hispanics remains low which prevents their movement into high-skilled trades. These challenges represent substantial changes in construction industry workforce which can make the problem of skilled labor availability critical.

This fundamental problem cannot be expected to ameliorate unless these challenges are addressed not only within the construction industry but also in K-12 education and societal perceptions towards construction. However, understanding the level of impact that craft shortages are having on project performance through robust statistical analyses may serve as a primary step in developing motivation for industry leaders, communities and construction stakeholders to address this challenge.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1. Findings

This research aimed to identify the influence of craft workers variability on specific construction project performance of safety, schedule, productivity and cost. The main objectives of the study were defined as follows:

1. Identify whether there is a significant difference in performance parameters of projects that reported a craft worker shortage versus those that did not.

2. Determine whether there is significant association between craft worker recruiting difficulty and performance parameters in projects.

3. Develop models that quantifiably links project craft worker variability to project performance parameters.

The paper No.1 presented in Chapter 2, achieves objectives 1-3 by examining the project safety performance parameter (TRIR) through several statistical analyses. The Poisson regression model demonstrates the significant relationship between increased craft recruiting difficulty and increased TRIR. The model is the first model that quantifiably links project craft worker availability to construction project safety performance.

The paper No.2 presented in Chapter 3 demonstrates that project productivity declines substantially when there is a shortage of craft labor. It shows that project managers tend to compensate its impact on project schedule using more overtime. However, the study demonstrates that even with the usage of more overtime, the impact of craft shortage on project schedule is considerable and cannot be eliminated completely. The paper achieves objective 1-3 as defined before, however due to the relatively low R^2 value in simple

regression models presented in this study, the models are considered as informative rather than predictive models.

The paper No.3 which is built on the foundation of Paper No.1 & 2, first quantitatively demonstrates different processes and overall impact that shortage of skills poses on project cost performance. Then using the statistical methods for combining data, two data sources were combined to obtain more accurate and robust predictive risk tool to forecasting the risk of shortage of skills on cost overrun. Therefore, the study achieves all three defined objectives. The final model is a risk tool model which links project cost overrun to the project craft staffing difficulty.

5.2. Limitations of the study

While the study provides beneficial and statistically valid results, it is recognized that it is subject to the following limitations:

1) The tool is based heavily on industrial projects and it is only based on projects performed in the U.S. and Canada, hence caution should be exercised when using the tool for projects outside of these characteristics.

2) The tool's performance estimates are based on a sample of past projects performed between 2001 and 2014 in North America, therefore the model needs to be reviewed and updated from time to time.

3) Although the model presented in Paper No.2 (Chapter 3) are statistically significant, as they are simple linear regression models with a relatively low number of data points and relatively low R^2 value, they should be considered as informative rather than predictive models. The other models presented in Paper No.1 and 3 are predictive risk

tools and should be used only to predict the risk associated with the shortage of skills in a project.

5.3. Research Contributions

Considering the results and conclusions in each paper presented in chapter 2-4, the study's contributions to the body of knowledge are as follow:

1) The study supports the assertion that a shortage of skilled workers exists at least in some segments of the North American construction industry. There are some specific regions such as Southeast and Southwest regions and some specific trade such as welders, pipe fitters, and electricians that currently experience this shortage more than other regions/trades. However, it can be stated that the construction professionals across the U.S. consider craft shortage as one of the main challenge in this industry and they perceive its impact on construction projects performance is substantial.

2) Project safety performance can be significantly declined if the project is executed with less skilled/experienced craft workers. The study presented in Chapter 2 demonstrates that there is an exponential association between increased craft worker recruiting difficulty and increased TRIR. Although there has been a significant long-term gain in construction safety within the United States, the quantitative analyses presented herein indicate a strong possibility that more safety incidents will occur in construction industry unless the shortages are reversed or innovative construction means and methods will be developed and adopted to work in a safe manner with a less qualified workforce.

3) The project productivity performance can be significantly declined if project performed under the shortage of skilled workers circumstances. This decline in productivity will contribute to the increase in cost and time of a project. Although the prevalent option of using more overtime can compensate the impact on time performance, it cannot eliminate the time overrun due to the shortage of skills. The study shows that there is significant association between increased in craft recruiting difficulty and increased in time overrun.

4) Predicting the cost allowance due to the shortage of skills in a project is critical for project estimators and planners. The RSMeans (2016) suggests the cost allowance of 10% of the total construction cost for Building projects and 11% for Heavy Industrial projects. This estimation does not consider the level of shortage and the size of project. Based on robust statistical analysis, this study provides the more precise tool which forecast the cost overrun in projects with regards to the level of craft recruiting difficulty and actual construction cost of project.

5.4. Opportunities for Future Research

Regarding the limitations and findings of the study, the followings are recommended for future research:

1) Since the labor-intensive projects such as mechanical projects can be impacted more when encountering craft shortage, it is suggested that this influential relationship is investigated specifically for these projects. In this way, a more precise risk tool can be obtained which can be used to predict a project performance based on availability of craft shortage.

2) For some trade-specific or project-specific that shortage is expected to be higher in a specific region, it is suggested that the impact of shortage of skills on a specific productivity measurement in these trades and/or projects is calculated.

3) Although in the paper No.3, it is shown that project quality can be impacted by shortage of craft labor, the study lacks the analysis of the impact of craft shortage on amount of rework. It is suggested that this analysis will be conducted particularly for projects which are more prone to the rework.

APPENDICES

Appendix A

(part of CII BM&M questionnaire that used in this study)

CII

The Knowledge Leader for Project Success
Owners · Contractors · Academics

Benchmarking & Metrics

Project Level Survey

Version 11

(Large Project Questionnaire)

1.1 Project Description

Which of the following best describes industry group for this project?

☐ Heavy Industrial	☐ Light Industrial
☐ Chemical Manufacturing	☐ Automotive Manufacturing
☐ Electrical (Generating)	☐ Consumer Products
☐ Environmental	Manufacturing
☐ Metals Refining/Processing	☐ Foods
☐ Mining	☐ Microelectronics
☐ Tailing	Manufacturing
☐ Natural Gas Processing	☐ Office Products
☐ Oil/Gas Exploration/Production	Manufacturing
(well-site)	☐ Pharmaceutical
☐ Oil Refining	Manufacturing
☐ Oil Sands Mining/Extraction	☐ Pharmaceutical Labs
☐ Oil Sands SAGD	Pharmaceutical Warehouse
☐ Oil Sands Upgrading	☐ Clean Room (Hi-Tech)
☐ Cogeneration	☐ Other Light Industrial
☐ Pulp and Paper	
☐ Other Heavy Industrial	
☐ Buildings	☐ Infrastructure
☐ Communications Center	☐ Airport
☐ Courthouse	☐ Central Utility Plant
☐ Dormitory/Hotel/Housing/Residential	☐ Electrical Distribution
☐ Embassy	☐ Flood Control
☐ Low rise Office (≤3 floors)	☐ Highway (including heavy
☐ High rise Office (>3 floors)	haul road)
☐ Hospital	☐ Marine Facilities
☐ Laboratory	☐ Navigation
☐ Maintenance Facilities	☐ Process Control

☐ Movie Theatre	☐ Rail
☐ Parking Garage	☐ Tunneling
☐ Physical Fitness Center	☐ Water/Wastewater
☐ Prison	☐ Telecom, Wide Area
☐ Restaurant/Nightclub	Network
☐ Retail Building	☐ Pipeline
☐ School	☐ Tank farms
☐ Warehouse	☐ Gas Distribution
☐ Other Buildings	☐ Other Infrastructure

1.2 Project Nature

From the list below, please select the category that best describes the primary nature of this project. Please see the glossary for definitions.

☐ Grass Roots, Greenfield

☐ Brownfield (co-locate)

☐ Modernization, Renovation, Upgrade (changes to existing capacity)

☐ Addition, Expansion

☐ Other Project Nature

Project Cost

Baseline Budget (Including Contingency)	Amount of Contingency in Budget	Actual Cost
$_____	$_____	$_____

Phase Cost

Project Function	Baseline Budget (Including Contingency)	Amount of Contingency in Budget	Actual Cost
Construction	$_____ ☐ NA ☐ Don't Know	$_____ ☐ NA ☐ Don't Know	$_____ ☐ NA ☐ Don't Know

Execution Schedule

	Baseline Schedule		Actual Schedule	
	Start mm/dd/yyyy	Stop mm/dd/yyyy	Start mm/dd/yyyy	Stop mm/dd/yyyy
Execution Schedule	_____ ☐ NA ☐ Don't Know	_____ ☐ NA ☐ Don't Know	_____ ☐ NA ☐ Don't Know	_____ ☐ NA ☐ Don't Know

Schedule by Phase

Project Function	Baseline Schedule		Actual Schedule	
	Start mm/dd/yyyy	Stop mm/dd/yyyy	Start mm/dd/yyyy	Stop mm/dd/yyyy
Construction	_____ ☐ NA ☐ Don't Know	_____ ☐ NA ☐ Don't Know	_____ ☐ NA ☐ Don't Know	_____ ☐ NA ☐ Don't Know

I. Workhours and Accident Data

In the spaces below, please record the **safety statistics** for this project.

1) Use the U.S. Department of Labor's OSHA definitions for recordable injuries among this project's workers. If you do not track in accordance with these definitions, click Don't Know in the boxes below.

2) A consolidated project OSHA 300 log is the best source for the data.

Note: for the CM tracking the safety data for the project, please report the safety statistics of the whole project, or skip this section.

   a.   Total site work hours   _____   ☐ Don't Know

   b.   Total Number of first aids

          _____ Cases   ☐ Don't Know

   c.   Total OSHA Number of Recordable Incident Cases (Injuries, Illnesses, Fatalities, Transfers and Restrictions)

          _____ Cases   ☐ Don't Know

   d.   Total Number of OSHA DART Cases (Days Away, Restricted or Transferred)

          _____ Cases   ☐ Don't Know

   e.   Total Number of Fatality Cases

          _____ Cases   ☐ Don't Know

   f.   Please indicate the number of Workman Compensation Claims on this project.

          _____ Cases   ☐ Don't Know

   g.   Please indicate the total dollar value of Workman Compensation Claims on this project.

          _____ Cases   ☐ Don't Know

   h.   Percentage of Overtime Hours

_____% ☐ Don't Know

"**Overtime**" - above 40 work hours a week. For example, if working 55 hours a work, so the overtime is 15 hours and the percentage of overtime hours is calculated as 15 hours overtime / 55 hours worked = 27.3% overtime. If the actual percentage cannot be calculated, please provide your best assessment. Answer Don't Know only if you cannot make a reasonable assessment.

II. Project Impact Factors

Using a scale from -5 to +5, where -5 means "an extremely negative impact" compared to what was expected or planned and +5 means an "extremely positive impact" compared to what was expected or planned, please indicate the extent to which each of the following factors had a net positive impact, a net negative impact, or was essentially as planned?

	Extremely Negative					As Planned					Extremely Positive
	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
Labor Disruption	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Availability of Skilled Labor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

APPENDIX B

RT-318 SURVEY TOOL

Construction Industry Craft Training
Construction Industry Institute
RT-318 Craft Availability Survey

A shortage of skilled, qualified craft professionals has been an unfortunate recurring trend in the North American construction industry for the past three decades. This has been an often-studied issue by both academic and industry organizations during this time period with various estimates of the magnitude and impact of craft shortages on project performance. While a review of the literature may suggest that the industry has experienced a prolonged craft shortage for the past three decades, the 2008 Great Recession was at least one period when the shortage was alleviated, indicating that the craft shortage may be a cycle that mirrors industry growth and slowdown trends. What is unknown is when there is industry or regional craft shortages, what are their impacts on a specific project's safety, cost, schedule, and quality performance?

The Construction Industry Institute (CII), a national research network funded by industry and housed at the University of Texas, has awarded a research grant to professors Tim Taylor of the University of Kentucky and Paul Goodrum of the University of Colorado at Boulder to investigate this issue. Working with an industry advisory team, CII Research Team 318 developed this questionnaire to be completed by a national sample of construction project managers and project controllers to quantify the influence that craft availability has on construction performance. Identifying how craft availability impacts construction performance will be a significant step towards helping future projects better understand how to adjust their project estimates and plan for potential work force shortages on their projects. The results of this survey will be used to develop a model to help estimate the impact of craft availability on project performance.

The Construction Industry Institute Research Team 318 developed this questionnaire to **be completed by a national sample of construction project managers and project controllers** to quantify the influence that craft availability has on construction performance. Your participation is purely voluntary. You do not have to participate and nothing will happen to you if you do not. **YOUR RESPONSES IN THIS SURVEY WILL BE KEPT STRICTLY CONFIDENTIAL.** The survey was pilot tested with a small sample of owner and construction firms prior to this national effort, and the pilot participants indicated that the survey should take approximately 90 minutes to complete. In exchange for completing this survey, you will be provided a copy of the project's research summary to be available in the Fall of 2015. If you would like a copy of the summary, please be sure to complete the request for the summary report on the last page. The survey Glossary of Terms is also provided at the end of this survey for your convenience. If you

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have any questions while completing the survey please contact one of the principal investigators:

Part I – Background

The following information is needed to compare different groups of projects from across the United States and Canada.

1. How many years have you worked in the construction industry? _____

2. What type of organization do you work for?
☐ Construction firm   ☐ Owner   ☐ Other (please describe)
_____

3. Which of the following best describes your current position?
☐ Project Manager   ☐ Human Resource   ☐ Construction Site Manager   ☐ Estimator   ☐ Project Controls Engineer

Please answer parts II - IV of the survey based on your most recently completed project.

Part II – Project Information and Performance Data

4. The craft workforce on your project was primarily:
☐ Union   ☐ Open Shop   ☐ Both

5. From the list below, please select the category that best describes the primary nature of this project? Please see the glossary for definitions

☐ Grass Roots, Greenfield ☐ Brownfield (co-locate) ☐ Modernization, Renovation, Upgrade (changes to existing capacity)
☐ Addition, Expansion   ☐ Other project nature, please describe
_____

6. Project description –Which of the following best describes the industry group for this project?

☐ Heavy Industrial	☐ Light Industrial
☐ Chemical Manufacturing ☐ Electrical (Generating) ☐ Environmental ☐ Metals Refining/Processing ☐ Mining ☐ Tailing ☐ Natural Gas Processing ☐ Oil/Gas Exploration/Production (well-site) ☐ Oil Refining ☐ Oil Sands Mining/Extraction ☐ Oil Sands SAGD ☐ Oil Sands Upgrading ☐ Cogeneration ☐ Pulp and Paper ☐ Other Heavy Industrial	☐ Automotive Manufacturing ☐ Consumer Products Manufacturing ☐ Foods ☐ Microelectronics Manufacturing ☐ Office Products Manufacturing ☐ Pharmaceutical Manufacturing ☐ Pharmaceutical Labs ☐ Pharmaceutical Warehouse ☐ Clean Room (Hi-Tech) ☐ Other Light Industrial

☐Buildings	☐Infrastructure
☐Communications Center ☐Courthouse ☐Dormitory/Hotel/Housing/Residential ☐Embassy ☐Low rise Office (≤3 floors) ☐High rise Office (>3 floors) ☐Hospital ☐Laboratory ☐Maintenance Facilities ☐Movie Theatre ☐Parking Garage ☐Physical Fitness Center ☐Prison ☐Restaurant/Nightclub ☐Retail Building ☐School ☐Warehouse ☐Other Buildings	☐Airport ☐Central Utility Plant ☐Electrical Distribution ☐Flood Control ☐Highway (including heavy haul road) ☐Marine Facilities ☐Navigation ☐Process Control ☐Rail ☐Tunneling ☐Water/Wastewater ☐Telecom, Wide Area Network ☐Pipeline ☐Tank farms ☐Gas Distribution ☐Other Infrastructure

7. Project Location (US State or Canadian Province):
_____

8. Budgeted and Actual Construction Costs. If you know the total construction costs but have incomplete information, you may enter as much information as you know. Please indicate whether the costs are in U.S. or Canadian Dollar (either is fine). Only enter data for your scope of work.

What was the total project budget for construction? (This amount should include contingency and correspond to the estimate at the time of contract award. This is the original baseline budget at the time of authorization and should <u>not</u> include any change orders).

_____
_____

Please check boxes if they are included in the total project budget: ☐ Labor   ☐ Material   ☐ Equipment

What was the total actual construction phase cost? (This cost should <u>include</u> amounts expended for in-house salaries, overhead, travel, and other indirect costs, but it should <u>exclude</u> the cost of land). _____

9. Planned and Actual Construction Schedule. Please enter as much schedule information as you know. Please use mm/dd/yy format for all dates.

What was the project's scheduled **construction** start date at project authorization (mm/dd/yy)
_____

What was the project's scheduled **construction** end date at project authorization (mm/dd/yy)
_____

What was the project's **construction** actual schedule start date (mm/dd/yy)
_____

What was the project's **construction** actual schedule stop date (mm/dd/yy)
_____

10. Project Safety Performance.

Please provide the following safety performance information for your ***project*** for your direct
hires only. A consolidated project OSHA 300 log is the best source for this data.

What was the OSHA total number of recordable incident cases (injuries, illnesses, fatalities,
transfers, and restrictions)?
_____

What was the number of OSHA DART cases (Days Away, Restricted or Transferred)?
_____

What were the actual direct work hours for the project? Craft work hours: _____ Owner
hours_____

11. Company Safety Performance.
In order to understand how the project's safety performance compared to the overall company's
safety performance, please provide the following safety performance information for your
company.

What is your company's OSHA Total Recordable Incidence Rate (TRIR) per 200,000 work-
hours for the last year of the project? _____

12. Productivity Performance.
In order to estimate your project's productivity performance factor (PF), what was your
project's estimated total craft work-hours? This data will be used in conjunction to your
actual craft work hours asked in question 10 to estimate your project's
PF_____

Part III – Craft Demand on Your Current Project
The following information is needed to identify how project parameters influence project staffing
requirements.

13. Workforce Information. The following table asks for the estimated number of hires, wages,
and per-diem rates at the start of construction for various trades. In addition, it asks for actual
hires, wages, and per-diem rates experienced during the course of construction. **If you know the
exact information, please enter it. Otherwise, please estimate the information as best as you
can. Please check the appropriate box:**

☐ **Exact information**   ☐ **Estimated information**

	Estimated number of peak craft	Actual number of peak craft	Actual number of total hires	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
						Min	Max	Min	Max
Carpenter									
Pipefitter									
Electrician									
Boilermaker									
Sheet metal									
Ironworker									
Pipe welder									
Structural welder									
Equipment Operator									
Crane Operator									
Millwright									
Instrument fitter									
Supervisors									

14. Workforce Turnover and Qualifications. The following table asks for the voluntary turnover rate, apprentice to journeyman ratio, and percentage of certified crafts for various trades. **If you know the exact information, please enter it. Otherwise, please estimate the information as best as you can. Please check the appropriate box: ☐ Exact information ☐ Estimated information**

	Voluntary Turnover Rate[1]	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified through either a Department of Labor approved union program, Licensed, NCCER, Red Seal, or other certification program[2]
Carpenter				
Pipefitter				
Electrician				
Boilermaker				
Sheet metal				
Ironworker				
Pipe welder				
Structural welder				
Equipment Operator				
Crane Operator				
Millwright				

Instrument fitter				
Supervisors				

1. Voluntary turnover is defined as an instance when an employer loses an employee due to the choice of the employee.

2. Certification information would likely be available through your Human Resources department.

15. Were any of the following strategies used on the project in order to address issues involving craft availability? (Please check all that apply)

☐ Retention bonus ☐ Increased base wages ☐ Increased per-diem ☐ Lodging facilities

☐ Completion bonuses ☐ Hire in bonus ☐ Prefabrication ☐ Other (Please Explain):
_____
_____

Part IV – Craft Availability on your Project

16. Did a workforce shortage impact your project's construction performance?

☐ Yes ☐ No (if your answer is No, please continue to the Question 18)

17. What was **level of the negative impact of the craft shortage** among the following performance parameters?

	No Impact	Slight (Craft issues lead to the consumption of float, contingency, or increased near misses)	Moderate (Craft issues lead to project delays, cost overruns, or OSHA recordable injuries)	Severe (Craft issues lead to significant project delays, cost overrun, or severe injury or fatality)
Cost				
Schedule				
Safety				
Rework				

18. Indicate the level of impact staffing difficulties had on this project among the following trades?

	No difficulty (There was no shortage. Able to staff the project with no delay on construction)	**Slight** (Staffing difficulties led to consumption of schedule float and/or contingency)	**Moderate** (Staffing difficulties led to delay of completing project activities on time)	**Severe** (Staffing difficulties led to delay of completing project milestones)	**Very Severe** (Staffing difficulties led to project delay)
Carpenter					

Pipefitter					
Electrician					
Boilermaker					
Sheet metal					
Ironworker					
Pipe welder					
Structural welder					
Equipment Operator					
Crane Operator					
Millwright					
Instrument fitter					
Supervisors					

19. Among the following trades, what percentage of the total hires involved personnel with **less skill and/or experience** (e.g. helper or apprentice or other trade) **than expected**?

	None 0%	To Some Degree <25%	Moderate 25 to less than 50%	Very Much 50 to less than 75%	Almost Completely 75 to less than 100%	All 100%
Carpenter						
Pipefitter						
Electrician						
Boilermaker						
Sheet metal						
Ironworker						
Pipe welder						
Structural welder						
Equipment Operator						
Crane Operator						
Millwright						
Instrument fitter						
Supervisors						

20. Among the following trades, while it may be difficult please estimate as best you can, what percentage of the total hires involved **"team hiring"** in which collection of craft workers with prior experience of working together on overall past projects are hired together?   For example, an ironworking foreman may have a group of ironworkers that follow him from job to job. (If you do not have this information yourself, it is likely available through your company's human resource group)

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	Do not know	None 0%	Minor Amount <25%	Fair Amount 25 to less than 50%	Moderate Amount 50 to less than 75%	Almost Completely 75 to less than 100%	All 100%
Carpenter							
Pipefitter							
Electrician							
Boilermaker							
Sheet metal							
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors							

Part V – Contact Information and Request for Summary Report

May we contact you for additional information?
☐ Yes   ☐ No

Would you like to receive a copy of the summary report?
☐ Yes   ☐ No

If you answered yes to either of the above questions, please provide the following contact information.

Name: _____
Company: _____
Email: _____
Fax: _____
Phone Number: _____

For more information on this survey please contact Tim Taylor by email at tim.taylor@uky.edu

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o **Actual Project Cost:** This is the total actual cost of a project. For contractors, the cost includes all work performed by the company including cost attributable to work added or deducted by change order. For owners, it excludes the cost of land, and any site preparation coast.

o **Actual number of total hires:** It is the total number of different craftsmen hired during the project.

o **Addition**: A new addition that ties in to an existing facility, often intended to expand capacity. Synonym: Expansion, Add-on

o **Brownfield:** The expansion, redevelopment, or reuse of property or facility which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant. Common examples are abandoned gas stations and dry cleaners, railroad properties, factories and closed military bases. Synonym: co-locate.

o **Building**: Includes Communications Center, Courthouse, Dormitory, Hotel, Large apartment complex, Embassy, Office building, Hospital, Laboratory, Maintenance Facilities, Movie Theatre, Parking Garage, Physical Fitness Center, Prison, Restaurant, Nightclub, Retail Building, School, and Warehouse.

o **Completion bonuses:** A monetary bonus paid to craft workers who work on the project for a defined period of time. The completion bonus is paid at the end of the project.

o **Construction start date:** It is the date for commencement of the first main activity in the site such as foundations or driving piles.

o **Construction stop date:** It is the date of substantial completion. It is the point in time when a facility is capable of being operated although some trim, insulation, and painting may still be needed. This occurs after completion of precommissioning. In some industries, substantial completion may have the same general meaning as beneficial occupancy.

o **Contingency**: All costs in contingency accounts including but not limited to normal contingency, allowances, reserves, indirect costs for schedule contingency, escalation, etc.

o **Days Away Restricted or Transferred (DART) Case:** An incident which results in days away from work, restricted work activity, or job transfer.

o **Direct Work Hours:** For the convenience of data collection, direct work hours include work hours of engineers/technician who produce engineering deliverables, include site investigators, meetings, planning, constructability, RFI, etc, and rework. Or work hours of workers who physically install material or physically assisting in installation.

o **Expansion:** A new addition that ties in to an existing facility, often intended to expand capacity. Synonym: Addition.

o **Grass Roots:** A new facility from the foundations and up. A project requiring demolition of an existing facility before new construction begins is also classified as grass roots. Synonym: Greenfield.

- **Heavy Industry**: Includes Chemical Manufacturing, Electrical (Generating), Gas Distribution, Environmental, Metals Refining/Processing, Mining, Natural Gas Processing, Oil Exploration/Production, Oil Refining, Oil Sands Mining/Extraction, Oil Sands SAGD, Oil Sands Upgrading, Cogeneration, Pulp and Paper, Others.

- **Infrastructure:** Includes Airport, Electrical Distribution, Flood Control, Highway, Marine Facilities, Navigation, Pipeline, Rail, Tunneling, Water/Wastewater, Telecom, and Wide Area Network.

- **Involuntary Turnover:** also referred to as termination, layoff, firing or discharge, it is employee termination of work initiated by employer.

- **Light Industry**: Includes Automotive Manufacturing, Consumer Products Manufacturing, Foods, Microelectronics Manufacturing, Office Products Manufacturing, Pharmaceutical Manufacturing, Pharmaceutical Labs, and Clean Room.

- **Modernization**: A facility for which a substantial amount of the equipment, structure, or other components is replaced or modified, and which may expand capacity and/or improve the process or facility. Synonyms: Renovation, Upgrade.

- **NCCER:** It is a not-for-profit education foundation created in 1996 as The National Center for Construction Education and Research. NCCER develops standardized construction and maintenance curricula and assessments with portable credentials. These credentials are tracked through NCCER's National Registry which allows organizations and companies to track the qualifications of their craft professionals and/or check the qualifications of possible new hires. The National Registry also assists craft professionals by maintaining their records in a secure database

- **Peak Craft:** the maximum number of craft workers on site for a single day on the project.

- **Recordable Incident*:* A recordable incident is a work-related illness and any injury which results in loss of consciousness, restriction of work or motion, transfer to another job, or requires medical treatment beyond first aid.

- **Red Seal:** The Red Seal Program is recognized as the interprovincial standard of excellence in the skilled trades. The program was established more than 50 years ago to provide greater mobility across Canada for skilled workers. Through the program, tradespersons are able to obtain a Red Seal endorsement on their provincial/territorial certificates by successfully completing an interprovincial Red Seal examination. The Red Seal Program acknowledges their competence and ensures recognition of their certification throughout Canada without further examination

- **Renovation**: A facility for which a substantial amount of the equipment, structure, or other components is replaced or modified, and which may expand capacity and/or improve the process or facility. Synonyms: Modernization, Upgrade.

- **Total actual construction cost:** All costs associated with the construction phase of the project.

- **Turnaround**: The period during which a boiler, generating unit, transmission line, or other facility is shut down and unable to perform its normal operations. The shutdown of a facility including for maintenance, inspection, testing, regulatory changes, or, in some cases, for

refueling is known as a planned shutdown. Turnaround is interchangeable with shutdown or outage depending on industry groups.

- o **Voluntary Turnover:** an instance when an employer loses an employee due to the choice of the employee.

APPENDIX C

RT-318 SURVEY DATA

Project No.	Number of Years' Experience of Respondent (yr.)	Type of Organization	Position of Respondent	Craft Workforce
1	7	Construction	Project Manager	Open Shop
2	28	Construction	Site Manager	Open Shop
3	41	Construction	Site Manager	Open Shop
4	31	Construction	Project Manager	Open Shop
5	22	Federal Government	Site Manager	Both
6	23	EPC Firm	Operations Manager	Open Shop
7	4	Owner	Project Manager	Open Shop
8	6	EPC Firm	Project Manager	Open Shop
9	26	Construction	Site Manager	Open Shop
10	9	Construction	Financial Control	Union
11	22	Owner	Project Controls	Union
12	17	Construction	Human Recourse	Open Shop
13	12	Construction	Project Controls	Open Shop
14	25	Construction	Project Manager	-
15	45	Construction	Vice President	Union
16	30	Construction	Project Controls	Union
17	9	Construction	Project Controls	Open Shop
18	30	Owner	Project Controls	Open Shop
19	10	General Contractor	Project Manager	Open Shop

20	50	Construction	Project Manager	Both
21	9	Construction	Project Manager	Union
22	39	Owner	Site Manager	Open Shop
23	25	Government Self-Performing	Director of Construction	Both
24	40	Construction Management	Construction Department Manager	Both
25	-	Owner	Project Manager	Union
26	47	EPC Firm	Construction Planning	Union
27	32	Owner	Project Manager	Open Shop
28	25	EPC Firm	Project Manager	Open Shop
29	30	Construction	Project Manager	Open Shop

Project No.	Nature of Project	Industry Group Project	Project Location
1	Greenfield	Heavy/Other	CA
2	Expansion	Heavy/Chemical	TX
3	Expansion	Heavy/Chemical	TX
4	Greenfield	Heavy/Chemical	TX
5	Modernization	Infrastructure/Elec Dist	DC
6	Brownfield/Addition	Heavy/Other	FL
7	Greenfield	Heavy/Natural Gas Processing	WY
8	Modernization	Heavy/Oil refining	NM
9	Brownfield/Addition	Heavy/Chemical	TN
10	-	Heavy/Electrical	MI
11	Modernization	Heavy/Mining	BC, Canada
12	Addition	Heavy	LA
13	Greenfield	Heavy/Chemical	LA
14	-	-	-
15	Greenfield	Heavy/Electrical	DE
16	Greenfield	Heavy/Oil refining	IN
17	Greenfield	Heavy/Electrical	MN
18	Greenfield	Heavy/Oil refining	TX
19	Addition	Infrastructure	WI
20	Addition	Light Industrial	NY
21	-	-	SK, Canada
22	Greenfield	Heavy/Electrical	NC
23	Modernization/Addition	Building/other	DC
24	Modernization	Heavy/Electrical	KS
25	Addition	Central Utility Plant	ON, Canada
26	Coal fired power plant retrofit	Central Utility Plant	AL
27	Capital	Chemical Plant	TX
28	Capital	Chemical Plant	NM
29	Grass Roots	Heavy/Oil Sands Mining	OK

Project No.	Project Budget ($M)	Actual Cost ($M)	Budget includes[1]
1	1070.00	1120.00	LME
2	45.00	45.00	LE
3	14.56	20.38	L
4	29.00	78.00	-
5	6.20	8.50	LME
6	488.00	399.00	LME
7	5.80	6.04	LME
8	4.60	3.60	LME
9	48.60	150.00	LME
10	42.00	57.00	LME
11	540.00	595.00	LME
12	-	250.00	LME
13	22.00	-	LE
14	14.92	14.93	LME
15	150.00	100.00	LME
16	154.00	320.00	L
17	17.30	16.30	LME
18	5379.00	8549.00	LME
19	29.80	27.00	LME
20	23.80	28.80	LME
21	6.60	9.22	LME
22	25.00	23.00	L
23	-	25/yr.	LME
24	30.00	28.70	LME
25	170.00	170.00	LME
26	37.00	76.00	LE
27	34.20	33.50	L/Sub
28	10.03	11.45	LME
29	59.6	148.60	LME

1. Labor (L), Material (M) , Equipment (E)

Project No.	Scheduled Start Date	Scheduled End Date	Actual Start Date	Actual Stop Date
1	20/02/2011	04/01/2014	26/03/2011	15/03/2014
2	05/04/2013	04/28/2013	21/06/2013	28/06/2014
3	04/01/2012	12/15/2012	15/06/2012	10/10/2013
4	03/01/2012	10/31/2012	03/01/2012	03/01/2014
5	05/23/2012	06/20/2013	06/04/2012	30/04/2014
6	01/03/2009	01/12/2010	01/04/2009	01/12/2010
7	08/22/2012	11/20/2012	09/10/2012	20/02/2013
8	08/01/2013	07/11/2014	12/08/2013	14/03/2014
9	04/01/2012	05/01/2013	01/04/2012	06/03/2014
10	15/10/2012	31/03/2014	01/12/2012	31/08/2014
11	27/01/2012	27/11/2013	01/05/2012	28/02/2014
12	01/07/2014	01/07/2016	01/07/2014	Ongoing
13	23/07/2012	01/05/2013	20/08/2012	24/10/2013
14	20/04/2013	17/12/2013	01/05/2013	31/12/2013
15	01/04/2013	01/05/2015	01/04/2013	Ongoing
16	01/04/2012	28/02/2013	01/04/2012	01/10/2013
17	12/07/2013	31/12/2013	15/07/2013	13/12/2013
18	15/09/2007	31/06/2010	21/08/2007	31/03/2012
19	03/09/2013	01/07/2014	03/09/2013	31/07/2014
20	20/06/2012	07/03/2013	11/08/2012	07/03/2013
21	01/05/2013	08/09/2014	01/05/2013	19/12/2014
22	01/06/2011	31/10/2012	01/06/2011	31/10/2012
23	-	-	-	-
24	01/09/2011	31/12/2013	01/11/2011	15/04/2014
25	10/10/2011	28/02/2014	01/11/2011	31/07/2014
26	10/09/2013	30/05/2014	17/09/2013	23/06/2014
27	01/11/2010	30/04/2012	01/10/2010	30/04/2012
28	01/03/2013	15/09/2013	01/03/2013	15/12/2013
29	13/09/2013	14/01/2014	13/09/2013	14/06/2014

Project No.	OSHA Number of Recordable Incident Cases	Number of OSHA DART Cases	Actual Direct Craft Work Hours (hr.)	Actual Direct Owner Work Hours (hr.)
1	14	0	3,777,869	-
2	0	0	380,000	-
3	1	0	320,000	20,000
4	0	0	1,150,000	-
5	0	0	-	68 hr/wk
6	3	0	-	-
7	0	0	17,250	1,440
8	0	0	18,475	-
9	1	0	308,447	-
10	2	0	333,000	-
11	19	0	1,835,562	85,493
12	-	-	1,000,000	-
13	2	2	474,399	-
14	1	0	72,914	-
15	2	0	321,000	15,000
16	-	-	2,270,000	-
17	1	0	69,874	-
18	174	-	-	-
19	0	0	21,500	-
20	0	0	13,328	1,000
21	5	0	58,600	-
22	1	0	457,000	34,000
23	5	-	-	-
24	3	2	86434	8643.4
25	35	-	717,580	70,265
26	4	0	750,000	42,000
27	0	0	648,000	670,000
28	0	0	30,731	-
29	3	0	133,750	2,700,000

Project No.	Company's OSHA Total Recordable Incidence Rate (TRIR) per 200,000 work-hours for the last year of the project	Estimated Craft Work Hours (hr.)
1	0.3	-
2	0	328,572
3	-	218,000
4	0.32	1,250,000
5	0.07	0
6	0.2	-
7	-	22,425
8	0	11,352
9	0.26	532,804
10	2	375,000
11	1.26	1,244,333
12	-	-
13	0.35	323,163
14	0.84	27,496
15	1.25	500,000
16	0.34	2,203,576
17	1.77	64,639
18	-	-
19	0.64	22,780
20	0	13,328
21	0.84	17,885
22	0.5	430,000
23	-	-
24	0.26	90,000
25	0	780,000
26	1.25	574,000
27	-	-
28	0.26	23,733
29	0.85	133,725

Project No.	Strategies for Craft Labor Availability Issue	Impact from Workforce Shortage
1	-	No
2	Increased base wages & per-diem	Yes
3	Increased base wages & Other	Yes
4	Retention and Completion Bonus	No
5	-	No
6	-	No
7	Increased base wages/per-diem	Yes
8	Increased per-diem	No
9	Prefabrication	Yes
10	-	No
11	Increased base wages	Yes
12	-	-
13	Increased base wages	Yes
14	-	No
15	Prefabrication	No
16	-	Yes
17	Retention	No
18	Retention/Increased base wages/per-diem	Yes
19	-	No
20	-	No
21	Retention/Increased base wages/per-diem& pre	Yes
22	Increased base wages	Yes
23	Hire in bonus	Yes
24	-	Yes
25	Lodging facilities	Yes
26	-	Yes
27	-	No
28	Competitive pay & per diem	Yes
29	Retention bonus/Completion bonuses	No

Project No.1

1.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter	300	400	220	275	37.48	37.48	45	70	45	70
Pipefitter	275	375	250	300	38.07	38.07	45	70	45	70
Electrician	200	400	150	250	37	37	45	70	45	70
Boilermaker	25	35	25	25	38.07	38.07	45	70	45	70
Sheet metal	0	0	0	0			45	70	45	70
Ironworker	250	350	200	275	35.25	35.25	45	70	45	70
Pipe welder	125	200	100	175	42.08	42.08	45	70	45	70
Structural welder	50	100	35	80	37.25	37.25	4	5	7	0
Equipment Operator	200	200	150	150	37.4	37.4	4	5	7	0
Crane Operator	20	30	15	25	44.75	44.75	4	5	7	0
Millwright	35	50	25	35	43.5	43.5	45	70	45	70
Instrument fitter	25	50	25	50	38.07	38.07	4	5	7	0
Supervisors	250	275	225	250	57.5	57.5	60	80	60	80

1.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	5	5	0.50	100
Pipefitter	15	5	0.50	100
Electrician	15	5	0.50	100
Boilermaker	1	0	1.00	100
Sheet metal				
Ironworker	5	5	0.50	100
Pipe welder	10	10	0.33	100
Structural welder	5	5	0.50	100
Equipment Operator	5	5	0.33	100
Crane Operator	5	0	0.25	100
Millwright	10	10	0.33	100
Instrument fitter	10	10	0.33	100
Supervisors	5	5		100

1.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

1.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter			x			
Electrician			x			
Boilermaker	x					
Sheet metal	x					
Ironworker	x					
Pipe welder			x			
Structural welder	x					
Equipment Operator	x					
Crane Operator	x					
Millwright	x					
Instrument fitter		x				
Supervisors	x					

1.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter							
Electrician		x					
Boilermaker	x						
Sheet metal	x						
Ironworker	x						
Pipe welder		x					
Structural welder	x						
Equipment Operator	x						
Crane Operator	x						
Millwright		x					
Instrument fitter	x						
Supervisors		x					

1.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter	x						
Pipefitter	x						
Electrician	x						
Boilermaker	x						
Sheet metal	x						
Ironworker	x						
Pipe welder	x						
Structural welder	x						
Equipment Operator	x						
Crane Operator	x						
Millwright	x						
Instrument fitter	x						
Supervisors			x				

- **Project No.2**

2.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter	5600									
Pipefitter	82107		80		28	30				
Electrician	25984		30		28	30				
Boilermaker	16749		20		28	30				
Sheet metal						0				
Ironworker	49334		35		20	30				
Pipe welder	27370		27		30	32				
Structural welder	8000		6		30	32				
Equipment Operator	11265		6		28	30				
Crane Operator	13829		6		30	32				
Millwright										
Instrument fitter	9277		11		30	32				
Supervisors	9494		8		35	38				

There is no data for Question No.14

2.17	No Impact	Slight	Moderate	Severe
Cost			x	
Schedule			x	
Safety		x		
Rework		x		

2.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter				x		
Electrician			x			
Boilermaker			x			
Sheet metal	x			x		
Ironworker			x			
Pipe welder						
Structural welder			x			
Equipment Operator		x				
Crane Operator		x				
Millwright		x				
Instrument fitter			x			
Supervisors			x			

2.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter		x					
Pipefitter				x			
Electrician			x				
Boilermaker			x				
Sheet metal		x					
Ironworker			x				
Pipe welder				x			
Structural welder			x				
Equipment Operator		x					
Crane Operator		x					
Millwright		x					
Instrument fitter			x				
Supervisors			x				

2.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter		x					
Pipefitter				x			
Electrician				x			
Boilermaker				x			
Sheet metal				x			
Ironworker				x			
Pipe welder					x		
Structural welder					x		
Equipment Operator				x			
Crane Operator				x			
Millwright				x			
Instrument fitter				x			
Supervisors					x		

- **Project No.3**

3.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter	30	45			24	26	0		60	
Pipefitter	60	126			25	26	0		60	
Electrician	25	36			25	26	0		60	
Boilermaker							0		60	
Sheet metal							0		60	
Ironworker	12	14			24	26	0		60	
Pipe welder	11	36			27	30	0		60	
Structural welder	4	4			27	28	0		6	
Equipment Operator	6	11			24	25	0		6	
Crane Operator	4	6			26	27	0		6	
Millwright	3	3			25	26	0		60	
Instrument fitter	7	12			26	26	0		6	
Supervisors	6	7					0		75	

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3.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	0.95	0.05	2.00	25
Pipefitter	0.7	0.3	3.00	30
Electrician	0.9	0.1	2.00	100
Boilermaker				
Sheet metal				
Ironworker	0.98	0.02	1.00	20
Pipe welder	0.9	0.1		100
Structural welder	0.95	0.05		100
Equipment Operator	0.8	0.2		100
Crane Operator	0.95	0.05		100
Millwright	1			60
Instrument fitter	0.95	0.05		70
Supervisors	0.98	0.02		

3.17	No Impact	Slight	Moderate	Severe
Cost			x	
Schedule			x	
Safety			x	
Rework			x	

3.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter		x				
Pipefitter				x		
Electrician			x			
Boilermaker						
Sheet metal						
Ironworker			x			
Pipe welder					x	
Structural welder			x			
Equipment Operator		x				
Crane Operator		x				
Millwright	x					
Instrument fitter			x			
Supervisors			x			

3.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter		x					
Pipefitter				x			
Electrician			x				
Boilermaker							
Sheet metal							
Ironworker			x				
Pipe welder				x			
Structural welder			x				
Equipment Operator		x					
Crane Operator		x					
Millwright		x					
Instrument fitter			x				
Supervisors			x				

3.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter					x		
Pipefitter			x				
Electrician					x		
Boilermaker							
Sheet metal							
Ironworker					x		
Pipe welder			x				
Structural welder			x				
Equipment Operator				x			
Crane Operator				x			
Millwright			x				
Instrument fitter				x			
Supervisors			x				

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- **Project No.4**

4.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter										
Pipefitter										
Electrician	370	1060	370	400	24	26	60	60	60	60
Boilermaker										
Sheet metal										
Ironworker										
Pipe welder										
Structural welder										
Equipment Operator										
Crane Operator										
Millwright										
Instrument fitter	20	80	20	50	26	27	60	60	60	60
Supervisors			100	100	36	36	100	100	100	100

4.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter				
Pipefitter				
Electrician	20%	50%	2 to 1	60
Boilermaker				
Sheet metal				
Ironworker				
Pipe welder				
Structural welder				
Equipment Operator				
Crane Operator				
Millwright				
Instrument fitter	20%	50%	3 to 1	0
Supervisors				

4.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

4.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter						
Pipefitter						
Electrician	x					
Boilermaker						
Sheet metal						
Ironworker						
Pipe welder						
Structural welder						
Equipment Operator						
Crane Operator						
Millwright						
Instrument fitter		x				
Supervisors	x					

4.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter							
Pipefitter							
Electrician			x				
Boilermaker							
Sheet metal							
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter			x				
Supervisors		x					

4.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter							
Pipefitter							
Electrician					x		
Boilermaker							
Sheet metal							
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter				x			
Supervisors							

- **Project No.5**

5.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		1				26.74				
Pipefitter		2				32.23				
Electrician		1				40.75				
Boilermaker		0								
Sheet metal		3				40.39				
Ironworker		1				28.83				
Pipe welder		0								
Structural welder		0								
Equipment Operator		0								
Crane Operator		0								
Millwright		0								
Instrument fitter		0								
Supervisors										

5.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	0	0	0.00	100
Pipefitter	0	0	0.25	100
Electrician	0	0	0.50	100
Boilermaker	0	0	0.00	
Sheet metal	0	0	0.67	100
Ironworker	0	0	0.00	
Pipe welder			0.00	
Structural welder	0	0	0.00	
Equipment Operator	0	0	0.00	
Crane Operator	0	0	0.00	
Millwright	0	0	0.00	
Instrument fitter	0	0	0.00	
Supervisors		0	0.00	

5.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

5.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter	x					
Electrician	x					
Boilermaker						
Sheet metal	x					
Ironworker	x					
Pipe welder						
Structural welder						
Equipment Operator						
Crane Operator						
Millwright						
Instrument fitter						
Supervisors						

5.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter	x						
Electrician	x						
Boilermaker							
Sheet metal	x						
Ironworker	x						
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors							

5.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter	x						
Pipefitter	x						
Electrician	x						
Boilermaker							
Sheet metal	x						
Ironworker	x						
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors							

- **Project No.6**

6.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		52		50	24		70		70	
Pipefitter		101			26		70		70	
Electrician		43			26		70		70	
Boilermaker							70		70	
Sheet metal							70		70	
Ironworker		55			26		70		70	
Pipe welder		90			24		70		70	
Structural welder		27			24		70		70	
Equipment Operator		46			24		70		70	
Crane Operator		15			26		70		70	
Millwright		6			26		70		70	
Instrument fitter		13			26		70		70	
Supervisors		60			34		70		70	

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6.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter			0.33	2
Pipefitter			0.50	17
Electrician			0.50	23
Boilermaker				
Sheet metal				
Ironworker			3.00	27
Pipe welder				2
Structural welder				7
Equipment Operator				4
Crane Operator				20
Millwright				0
Instrument fitter			0.50	15
Supervisors			0.11	13

6.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

6.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter						
Pipefitter						
Electrician						
Boilermaker						
Sheet metal						
Ironworker						
Pipe welder		very minor				
Structural welder						
Equipment Operator						
Crane Operator						
Millwright						
Instrument fitter						
Supervisors						

6.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter		x					
Pipefitter		x					
Electrician		x					
Boilermaker		x					
Sheet metal		x					
Ironworker		x					
Pipe welder		x					
Structural welder		x					
Equipment Operator		x					
Crane Operator		x					
Millwright		x					
Instrument fitter		x					
Supervisors		x					

6.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter			x				
Pipefitter			x				
Electrician			x				
Boilermaker			x				
Sheet metal			x				
Ironworker			x				
Pipe welder			x				
Structural welder			x				
Equipment Operator			x				
Crane Operator			x				
Millwright			x				
Instrument fitter			x				
Supervisors			x				

- **Project No.7**

7.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter					59.2		74	88.8		
Pipefitter	5	5	5	5	59.2		74	88.8		
Electrician	2	3	3	3	62.9		78.6	94.4		
Boilermaker										
Sheet metal										
Ironworker					59.2		74	88.8		
Pipe welder	5	5	5	5	98.6		118.3	142.9		
Structural welder	2	2	2	2	44.29					
Equipment Operator	2	2	2	2	59.2					
Crane Operator	2	2	2	2	74.1					
Millwright					62.9		78.6	94.4		
Instrument fitter	1	1	1	1	62.9					
Supervisors	5	5	5	5	97.6		122	146.4		

7.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter				
Pipefitter				
Electrician		1		100
Boilermaker				
Sheet metal				
Ironworker				
Pipe welder		3		100
Structural welder				
Equipment Operator				
Crane Operator				
Millwright				
Instrument fitter				
Supervisors				

7.17	No Impact	Slight	Moderate	Severe
Cost			x	
Schedule			x	
Safety	x			
Rework		x		

7.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter						x
Pipefitter	x					
Electrician		x				
Boilermaker						x
Sheet metal	x					
Ironworker	x					
Pipe welder				x		
Structural welder		x				
Equipment Operator		x				
Crane Operator	x					
Millwright						x
Instrument fitter	x					
Supervisors	x					

7.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter							x
Pipefitter		x					
Electrician				x			
Boilermaker							x
Sheet metal	x						
Ironworker	x						
Pipe welder					x		
Structural welder		x					
Equipment Operator		x					
Crane Operator				x			
Millwright							x
Instrument fitter		x					
Supervisors		x					

7.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter	x						
Pipefitter		x					
Electrician							x
Boilermaker	x						
Sheet metal	x						
Ironworker	x						
Pipe welder				x			
Structural welder	x						
Equipment Operator		x					
Crane Operator			x				
Millwright	x						
Instrument fitter							x
Supervisors			x				

- **Project No.8**

8.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter										
Pipefitter		4	26	25	26.54	25	50	70	40	60
Electrician		4	26	25	26.11	25	50	70	40	60
Boilermaker										
Sheet metal										
Ironworker		10	26	25						
Pipe welder		4	26	25	28.23	28	50	70	40	60
Structural welder										
Equipment Operator	2	2	26	25	46.94	30	50	80	40	60
Crane Operator	2	3	26	25	50.87	27	50	80	40	60
Millwright										
Instrument fitter										
Supervisors	8	9	26	25	55.1		80	80	50	80

8.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter				
Pipefitter	1	2	0.25	
Electrician	1	1	0.33	
Boilermaker				
Sheet metal				
Ironworker	3	5	0.20	
Pipe welder	1	4	0.25	
Structural welder				
Equipment Operator		2	0.50	
Crane Operator	1		0.50	
Millwright				
Instrument fitter				
Supervisors				

8.17	No Impact	Slight	Moderate	Severe
Cost	x			
Schedule		x		
Safety	x			
Rework	x			

8.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter						x
Pipefitter						x
Electrician						x
Boilermaker						x
Sheet metal						x
Ironworker						x
Pipe welder		x				
Structural welder						x
Equipment Operator						x
Crane Operator						x
Millwright						x
Instrument fitter						x
Supervisors						x

8.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter	x						
Electrician		x					
Boilermaker	x						
Sheet metal	x						
Ironworker	x						
Pipe welder	x						
Structural welder		x					
Equipment Operator	x						
Crane Operator	x						
Millwright	x						
Instrument fitter	x						
Supervisors		x					

8.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter		x					
Pipefitter			x				
Electrician		x					
Boilermaker		x					
Sheet metal		x					
Ironworker		x					
Pipe welder			x				
Structural welder				x			
Equipment Operator		x					
Crane Operator					x		
Millwright	x						
Instrument fitter		x					
Supervisors						x	

- **Project No.9**

9.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		12		12						
Pipefitter		50		50	26.57		7.85			7.85
Electrician		6		6	25.5		0			0
Boilermaker										
Sheet metal										
Ironworker		15		15	25		7.85			7.85
Pipe welder		30		30						
Structural welder		8		8	25					
Equipment Operator		5		5	25					
Crane Operator		3		3	28					
Millwright		5		5	26.57		7.85			7.85
Instrument fitter		12		12	26.57					
Supervisors		15		15	30	30	8.5			8.5

9.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter				0
Pipefitter	10	10		20
Electrician	0	1		0
Boilermaker				
Sheet metal				
Ironworker	4	2		100
Pipe welder	5	5		
Structural welder	2	0		
Equipment Operator	0	0		20
Crane Operator	0	0		100
Millwright	0	0		25
Instrument fitter	0	0		
Supervisors	0	0		60

9.17	No Impact	Slight	Moderate	Severe
Cost		x		
Schedule		x		
Safety		x		
Rework			x	

9.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter	x					
Electrician						
Boilermaker						
Sheet metal						
Ironworker	x					
Pipe welder	x					
Structural welder	x					
Equipment Operator	x					
Crane Operator	x					
Millwright	x					
Instrument fitter	x					
Supervisors	x					

9.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter							
Pipefitter		x					
Electrician							
Boilermaker							
Sheet metal							
Ironworker							
Pipe welder		x					
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors		x					

9.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter							
Pipefitter				x			
Electrician							
Boilermaker							
Sheet metal							
Ironworker					x		
Pipe welder				x			
Structural welder					x		
Equipment Operator							
Crane Operator					x		
Millwright				x			
Instrument fitter				x			
Supervisors				x			

• **Project No.10**

10.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter				20		29.76				
Pipefitter										
Electrician										
Boilermaker				62		36.4				
Sheet metal										
Ironworker				9		33.33				
Pipe welder										
Structural welder										
Equipment Operator				24		31.03				
Crane Operator										
Millwright				8		31.31				
Instrument fitter										
Supervisors										

• There is no data for Question No.14, 17, 18, 19 and 20.

- **Project No.11**

11.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter	47	178	47	74	76.65	75.34	20	130	20	130
Pipefitter	112	223	112	99	78.67	76.28	20	130	20	130
Electrician	134	418	134	158	78.71	76.15	20	130	20	130
Boilermaker										
Sheet metal	25	109	25	55	76.22	78.66	20	130	20	130
Ironworker	106	302	106	97	81.56	87.48	20	130	20	130
Pipe welder	63	75	63	23	88.02	86.96	20	130	20	130
Structural welder										
Equipment Operator	32	81	32	22	93.99	71.45	20	130	20	130
Crane Operator										
Millwright	46	123	46	57	78.98	78.43	20	130	20	130
Instrument fitter	41	99	41	51	78.83	73.48	20	130	20	130
Supervisors										

11.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	40	60	75.00	80
Pipefitter	30	70	31.00	100
Electrician	44	56	39.00	100
Boilermaker				
Sheet metal	32	68	36.00	30
Ironworker	42	58	52.00	100
Pipe welder	41	59	0.00	100
Structural welder	35	65	22.00	100
Equipment Operator	60	40	0.00	100
Crane Operator				
Millwright	39	61	32.00	100
Instrument fitter	28	72	61.00	100
Supervisors	58	42		100

17	No Impact	Slight	Moderate	Severe
Cost			x	
Schedule			x	
Safety		x		
Rework			x	

11.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter			x			
Electrician		x				
Boilermaker						x
Sheet metal		x				
Ironworker				x		
Pipe welder			x			
Structural welder			x			
Equipment Operator	x					
Crane Operator			x			
Millwright		x				
Instrument fitter				x		
Supervisors		x				

11.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter		x					
Pipefitter			x				
Electrician			x				
Boilermaker							x
Sheet metal		x					
Ironworker			x				
Pipe welder			x				
Structural welder		x					
Equipment Operator	x						
Crane Operator	x						
Millwright		x					
Instrument fitter		x					
Supervisors	x						

11.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter			x				
Pipefitter			x				
Electrician					x		
Boilermaker	x						
Sheet metal				x			
Ironworker					x		
Pipe welder	x						
Structural welder	x						
Equipment Operator			x				
Crane Operator		x					
Millwright			x				
Instrument fitter			x				
Supervisors			x				

• **Project No.12**

12.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter										
Pipefitter			200		28					
Electrician			-							
Boilermaker			0							
Sheet metal			0							
Ironworker			50		26					
Pipe welder			50		30					
Structural welder			20		26					
Equipment Operator			20		28					
Crane Operator			20		28					
Millwright			10		28					
Instrument fitter			-		-					
Supervisors			20		32					

• There is No Data for Question No.14, 17, 18, 19 and 20.

- **Project No.13**

13.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter	35	46	20	23	25	25		80		80
Pipefitter	245	300	191	210	26.5	25		80		80
Electrician										
Boilermaker										
Sheet metal										
Ironworker	55	78	43	61	25	25		80		80
Pipe welder	50	65	35	43	27	27		80		80
Structural welder	10	15	10	10	25	25		80		80
Equipment Operator										
Crane Operator	30	35	26	28	27	27		80		80
Millwright	45	20	35	12	25	25		80		80
Instrument fitter										
Supervisors										

13.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	15	5	1 to 2	10
Pipefitter	25	10	1 to 3	75
Electrician				
Boilermaker				
Sheet metal				
Ironworker	25	10	1 to 2	65
Pipe welder	30	15	1 to 1	100
Structural welder	10	10	1to 1	25
Equipment Operator				
Crane Operator	10	5	1 to 1	100
Millwright	5	5	1 to 2	80
Instrument fitter				
Supervisors	5	10	1 to 1	100

13.17	No Impact	Slight	Moderate	Severe
Cost			x	
Schedule			x	
Safety		x		
Rework			x	

13.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter						
Pipefitter		x				
Electrician						
Boilermaker						
Sheet metal						
Ironworker	x					
Pipe welder			x			
Structural welder		x				
Equipment Operator	x					
Crane Operator		x				
Millwright	x					
Instrument fitter						
Supervisors		x				

13.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter							
Pipefitter			x				
Electrician							
Boilermaker							
Sheet metal							
Ironworker		x					
Pipe welder			x				
Structural welder		x					
Equipment Operator							
Crane Operator		x					
Millwright		x					
Instrument fitter							
Supervisors			x				

13.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter							
Pipefitter			x				
Electrician							
Boilermaker							
Sheet metal							
Ironworker			x				
Pipe welder		x					
Structural welder		x					
Equipment Operator		x					
Crane Operator		x					
Millwright			x				
Instrument fitter							
Supervisors		x					

- **Project No.14**

14.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		4	4							
Pipefitter		80	60		51.12	70.1			50	
Electrician		40	40		60.46	61.58			50	
Boilermaker		6	8		57.89	68.82			50	
Sheet metal		6	6							
Ironworker		12	10		52.56	61.39			50	
Pipe welder										
Structural welder										
Equipment Operator										
Crane Operator										
Millwright		2	2							
Instrument fitter		2	2							
Supervisors		6	6		75	75				

14.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	minimal	minimal		0
Pipefitter	minimal	minimal	1 to 5	0
Electrician	minimal	minimal	1 to 5	0
Boilermaker	minimal	minimal		0
Sheet metal	minimal	minimal		0
Ironworker	minimal	minimal		0
Pipe welder				
Structural welder				
Equipment Operator				
Crane Operator				
Millwright	minimal	minimal		0
Instrument fitter	minimal	minimal		0
Supervisors	minimal	minimal		0

14.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

14.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter		x				
Electrician	x					
Boilermaker	x					
Sheet metal	x					
Ironworker	x					
Pipe welder						
Structural welder						
Equipment Operator						
Crane Operator						
Millwright	x					
Instrument fitter	x					
Supervisors	x					

14.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter	x						
Electrician	x						
Boilermaker							
Sheet metal	x						
Ironworker	x						
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright	x						
Instrument fitter	x						
Supervisors	x						

14.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter		x					
Pipefitter		x					
Electrician		x					
Boilermaker					x		
Sheet metal					x		
Ironworker					x		
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright		x					
Instrument fitter						x	
Supervisors							x

- **Project No.15**

15.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter			15							
Pipefitter			85							
Electrician			45							
Boilermaker			80							
Sheet metal										
Ironworker			20							
Pipe welder										
Structural welder										
Equipment Operator			5							
Crane Operator			12							
Millwright			12							
Instrument fitter										
Supervisors										

15.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	3	3		100
Pipefitter	2	6		100
Electrician	2	3		100
Boilermaker	2	8		100
Sheet metal				
Ironworker	2	4		100
Pipe welder				
Structural welder				
Equipment Operator	1	0		100
Crane Operator	2	4		100
Millwright	1	1		100
Instrument fitter				
Supervisors				

15.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

15.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter	x					
Electrician	x					
Boilermaker		x				
Sheet metal						
Ironworker	x					
Pipe welder						
Structural welder						
Equipment Operator	x					
Crane Operator	x					
Millwright	x					
Instrument fitter						
Supervisors						

15.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter		x					
Pipefitter		x					
Electrician	x						
Boilermaker		x					
Sheet metal							
Ironworker		x					
Pipe welder							
Structural welder							
Equipment Operator	x						
Crane Operator	x						
Millwright		x					
Instrument fitter							
Supervisors							

15.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter	x						
Pipefitter	x						
Electrician	x						
Boilermaker	x						
Sheet metal							
Ironworker	x						
Pipe welder							
Structural welder							
Equipment Operator	x						
Crane Operator							
Millwright	x						
Instrument fitter							
Supervisors							

- **Project No.16**

16.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		180	119	140	61.42	61.42				
Pipefitter		300	176	230	68.26	68.26				
Electrician		320	145	265	65.28	65.28				
Boilermaker		35	16	18	58.29	58.29				
Sheet metal		0	0	0	0	0				
Ironworker		50	30	30	64.58	64.58				
Pipe welder		150	75	102	68.26	68.26				
Structural welder		0	0	0	0	0				
Equipment Operator		45	5	25	60.3	60.3				
Crane Operator		20	5	74	64.55	64.55				
Millwright		30	6	15	61.37	61.37				
Instrument fitter		60	45	56	66.77	66.77				
Supervisors		105	57	79	60.35	60.35				

16.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	10	2	1 to15	
Pipefitter	15	10	1 to10	
Electrician	15	5	2 to15	
Boilermaker	5	5	0	
Sheet metal	0	0	0	
Ironworker	5	10	0	
Pipe welder	5	15	0	
Structural welder	0	0	0	
Equipment Operator	5	5	0	
Crane Operator	0	0	0	
Millwright	0	0	0	
Instrument fitter	0	0	0	
Supervisors	10	15	1 to15	

16.17	No Impact	Slight	Moderate	Severe
Cost			x	
Schedule			x	
Safety	x			
Rework		x		

16.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter				x		
Electrician			x			
Boilermaker	x					
Sheet metal						x
Ironworker	x					
Pipe welder			x			
Structural welder						x
Equipment Operator	x					
Crane Operator	x					
Millwright						
Instrument fitter	x					
Supervisors			x			

16.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter		x					
Electrician		x					
Boilermaker	x						
Sheet metal							x
Ironworker	x						
Pipe welder		x					
Structural welder							x
Equipment Operator	x						
Crane Operator	x						
Millwright	x						
Instrument fitter	x						
Supervisors	x						

16.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter			x				
Pipefitter					x		
Electrician					x		
Boilermaker				x			
Sheet metal	x						
Ironworker			x				
Pipe welder					x		
Structural welder	x						
Equipment Operator			x				
Crane Operator			x				
Millwright			x				
Instrument fitter				x			
Supervisors				x			

- **Project No.17**

17.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		2	10	8	24	22.5	70	70	70	70
Pipefitter		0	0	0	0	0	0	0	0	0
Electrician		0	2	3	24	22	70	70	70	70
Boilermaker		0	0	0	0	0	0	0	0	0
Sheet metal		0	0	0	0	0	0	0	0	0
Ironworker		3	14	15	42	22.5	70	70	70	70
Pipe welder		0	0	0	0	0	0	0	0	0
Structural welder		0	0	0	0	0	0	0	0	0
Equipment Operator		3	10	10	26	25	7			
Crane Operator		1	6	6	34	36	7	0	0	0
Millwright		4	14	15	24	22.5	70	70	70	70
Instrument fitter		0	0	0	0	0	0	0	0	0
Supervisors		0	10	12	35	35	70	70	70	70

17.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	2	1		
Pipefitter	0	0		
Electrician	0	0		
Boilermaker	0	0		
Sheet metal	0	0		
Ironworker	2	2		
Pipe welder	0	0		
Structural welder	0	0		
Equipment Operator	1	1		
Crane Operator	1	0		
Millwright	1	1		
Instrument fitter	0	0		
Supervisors	0	0		

17.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

17.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter						
Electrician	x					
Boilermaker						
Sheet metal						
Ironworker	x					
Pipe welder						
Structural welder						
Equipment Operator	x					
Crane Operator		x				
Millwright	x					
Instrument fitter						
Supervisors	x					

17.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter		x					
Pipefitter							
Electrician	x						
Boilermaker							
Sheet metal							
Ironworker		x					
Pipe welder							
Structural welder							
Equipment Operator	x						
Crane Operator		x					
Millwright	x						
Instrument fitter							
Supervisors	x						

17.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter		x					
Pipefitter							
Electrician		x					
Boilermaker							
Sheet metal							
Ironworker		x					
Pipe welder							
Structural welder							
Equipment Operator		x					
Crane Operator		x					
Millwright		x					
Instrument fitter							
Supervisors		x					

Project No.18

18.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		1730	290	384	25	24	60	60	30	30
Pipefitter		11689	1957	2567	27	26	60	60	30	30
Electrician		5391	903	1198	27	26	60	60	30	30
Boilermaker		384	64	85	27	26	60	60	30	30
Sheet metal					25	24	60	60	30	30
Ironworker		1720	288	382	25	24	60	60	30	30
Pipe welder		1152	193	256	25.75	30	60	60	30	30
Structural welder		998	167	222	25	27	6	0	3	0
Equipment Operator		2256	378	501	27	26	6	0	3	0
Crane Operator		527	88	117	27.75	27.75	6	0	3	0
Millwright		527	88	117	27	26	60	60	30	30
Instrument fitter		1413	237	314	27	29	6	0	3	0
Supervisors		5063	848	1125	32	33	60	60	30	30

18.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	8	n/a	3 to 5	
Pipefitter	10	n/a	4 to 4	
Electrician	8	n/a	4 to 4	
Boilermaker	8	n/a	3 to 5	
Sheet metal	8	n/a	3 to 5	
Ironworker	8	n/a	3 to 5	
Pipe welder	10	n/a	4 to 4	
Structural welder	8	n/a	4 to 4	
Equipment Operator	10	n/a	4 to 4	
Crane Operator	10	n/a	4 to 4	
Millwright	8	n/a	3 to 5	
Instrument fitter	10	n/a	4 to 4	
Supervisors	10	n/a	na	

18.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter		x				
Pipefitter				x		
Electrician			x			
Boilermaker		x				
Sheet metal	x					
Ironworker	x					
Pipe welder				x		
Structural welder		x				
Equipment Operator			x			
Crane Operator			x			
Millwright		x				
Instrument fitter			x			
Supervisors			x			

18.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter		x					
Pipefitter			x				
Electrician		x					
Boilermaker	x						
Sheet metal	x						
Ironworker		x					
Pipe welder				x			
Structural welder		x					
Equipment Operator		x					
Crane Operator			x				
Millwright		x					
Instrument fitter			x				
Supervisors			x				

18.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter	x						
Pipefitter	x						
Electrician	x						
Boilermaker	x						
Sheet metal	x						
Ironworker	x						
Pipe welder	x						
Structural welder	x						
Equipment Operator	x						
Crane Operator	x						
Millwright	x						
Instrument fitter	x						
Supervisors	x						

- **Project No.19**

19.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter										
Pipefitter										
Electrician										
Boilermaker			30	40	25	25	100	100	100	100
Sheet metal										
Ironworker										
Pipe welder										
Structural welder										
Equipment Operator										
Crane Operator										
Millwright										
Instrument fitter										
Supervisors			2	2	40	40	100	100	100	100

19.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter				
Pipefitter				
Electrician				
Boilermaker	10%	2%	n/a	merit employees
Sheet metal				
Ironworker				
Pipe welder				
Structural welder				
Equipment Operator				
Crane Operator				
Millwright				
Instrument fitter				
Supervisors	0%	0%	n/a	merit employees

19.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

19.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter						
Pipefitter						
Electrician						
Boilermaker	x					
Sheet metal						
Ironworker						
Pipe welder						
Structural welder						
Equipment Operator						
Crane Operator						
Millwright						
Instrument fitter						
Supervisors	x					

19.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter							
Pipefitter							
Electrician							
Boilermaker	x						
Sheet metal							
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors	x						

19.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter							
Pipefitter							
Electrician							
Boilermaker	x						
Sheet metal							
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors		x					

• **Project No.20**

20.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		40		9						
Pipefitter		36		17						
Electrician		28		17						
Boilermaker										
Sheet metal		21		5						
Ironworker		24		13						
Pipe welder										
Structural welder										
Equipment Operator										
Crane Operator										
Millwright		49		27						
Instrument fitter										
Supervisors		12		12						

• There is no Data for Question No.14 and 17.

20.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter	x					
Electrician	x					
Boilermaker						
Sheet metal	x					
Ironworker	x					
Pipe welder						
Structural welder						
Equipment Operator						
Crane Operator	x					
Millwright	x					
Instrument fitter						
Supervisors	x					

20.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter			x				
Pipefitter			x				
Electrician			x				
Boilermaker							
Sheet metal			x				
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright				x			
Instrument fitter							
Supervisors							

20.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter					x		
Pipefitter					x		
Electrician						x	
Boilermaker							
Sheet metal							x
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							x
Instrument fitter							
Supervisors							

- **Project No.21**

21.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter			2	2	18.26	18.26	150	150	150	150
Pipefitter			27	35	39.86	39.86	150	150	150	150
Electrician										
Boilermaker										
Sheet metal										
Ironworker										
Pipe welder										
Structural welder										
Equipment Operator										
Crane Operator										
Millwright										
Instrument fitter										
Supervisors										

21.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	3 ppl	0	n/a	-
Pipefitter	33 ppl	2 ppl	1 to 4	100
Electrician				
Boilermaker				
Sheet metal				
Ironworker				
Pipe welder				
Structural welder				
Equipment Operator				
Crane Operator				
Millwright				
Instrument fitter				
Supervisors				

21.17	No Impact	Slight	Moderate	Severe
Cost			x	
Schedule				x
Safety	x			
Rework		x		

21.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter		x				
Pipefitter				x		
Electrician						x
Boilermaker						x
Sheet metal						x
Ironworker						x
Pipe welder				x		
Structural welder						x
Equipment Operator						x
Crane Operator						x
Millwright						x
Instrument fitter						x
Supervisors						x

21.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter			x				
Electrician							x
Boilermaker							x
Sheet metal							x
Ironworker							x
Pipe welder			x				
Structural welder							x
Equipment Operator							x
Crane Operator							x
Millwright							x
Instrument fitter							x
Supervisors							x

21.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter		x					
Pipefitter			x				
Electrician							
Boilermaker							
Sheet metal							
Ironworker							
Pipe welder			x				
Structural welder							
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors							

- **Project No.22**

22.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter			15	15	20	22				
Pipefitter			30	30	23	25				
Electrician			40	40	23	25				
Boilermaker										
Sheet metal										
Ironworker			10	10	23	25				
Pipe welder										
Structural welder										
Equipment Operator			7	7	23	25				
Crane Operator			3	3	23	25				
Millwright			10	10						
Instrument fitter										
Supervisors			11	11	55	55				

22.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	4	2	5 to 1	
Pipefitter	4	2	5 to 1	
Electrician	4	2	5 to 1	
Boilermaker				
Sheet metal				
Ironworker	4	2	5 to 1	
Pipe welder				
Structural welder				
Equipment Operator	4	2		
Crane Operator	4	2		
Millwright				
Instrument fitter				
Supervisors	0	0		

22.17	No Impact	Slight	Moderate	Severe
Cost		x		
Schedule	x			
Safety	x			
Rework	x			

22.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter		x				
Electrician	x					
Boilermaker						
Sheet metal						
Ironworker	x					
Pipe welder						
Structural welder						
Equipment Operator	x					
Crane Operator	x					
Millwright	x					
Instrument fitter						
Supervisors	x					

22.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter		x					
Electrician	x						
Boilermaker							
Sheet metal							
Ironworker	x						
Pipe welder							
Structural welder							
Equipment Operator	x						
Crane Operator	x						
Millwright							
Instrument fitter							
Supervisors	x						

22.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter				x			
Pipefitter				x			
Electrician				x			
Boilermaker							
Sheet metal							
Ironworker				x			
Pipe welder							
Structural welder							
Equipment Operator			x				
Crane Operator			x				
Millwright			x				
Instrument fitter							
Supervisors			x				

- **Project No.23**

23.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		3	3	3	18					
Pipefitter		19	19	19	45					
Electrician										
Boilermaker										
Sheet metal										
Ironworker		3	3	3	29					
Pipe welder		9	9	9	24					
Structural welder		5	5	5	26.9					
Equipment Operator										
Crane Operator										
Millwright										
Instrument fitter										
Supervisors										

23.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	very low	very low	0:1	100
Pipefitter	low	low	0:1	100
Electrician				
Boilermaker				
Sheet metal				
Ironworker	none	none	0:1	100
Pipe welder	none	none	0:1	100
Structural welder	high	high	0:1	100
Equipment Operator				
Crane Operator				
Millwright				
Instrument fitter				
Supervisors				

23.17	No Impact	Slight	Moderate	Severe
Cost			x	
Schedule		x		
Safety	x			
Rework	x			

23.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter		x				
Pipefitter			x			
Electrician						
Boilermaker						
Sheet metal						
Ironworker		x				
Pipe welder			x			
Structural welder						
Equipment Operator					x	
Crane Operator						
Millwright						
Instrument fitter						
Supervisors						

23.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter		x					
Pipefitter		x					
Electrician							
Boilermaker							
Sheet metal							
Ironworker	x						
Pipe welder	x						
Structural welder						x	
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors							

23.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter		x					
Pipefitter		x					
Electrician							
Boilermaker							
Sheet metal							
Ironworker		x					
Pipe welder		x					
Structural welder		x					
Equipment Operator							
Crane Operator							
Millwright							
Instrument fitter							
Supervisors							

- **Project No.24**

24.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter										
Pipefitter										
Electrician		10	30	40	40	40	75	125	75	125
Boilermaker										
Sheet metal										
Ironworker										
Pipe welder										
Structural welder										
Equipment Operator		8	5	8	35	35				
Crane Operator		8	5	8	35	35				
Millwright										
Instrument fitter										
Supervisors		12	6	12	45	45	75	125	75	125

24.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter				
Pipefitter				
Electrician			1 to 2	75
Boilermaker				
Sheet metal				
Ironworker				
Pipe welder				
Structural welder				
Equipment Operator			1 to 2	75
Crane Operator			1 to 2	75
Millwright				
Instrument fitter				
Supervisors			1 to 4	90

24.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter						
Pipefitter						
Electrician			x			
Boilermaker						
Sheet metal						
Ironworker						
Pipe welder						
Structural welder						
Equipment Operator			x			
Crane Operator			x			
Millwright						
Instrument fitter						
Supervisors						

24.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter							
Pipefitter							
Electrician			x				
Boilermaker							
Sheet metal							
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator			x				
Crane Operator			x				
Millwright							
Instrument fitter							
Supervisors							

24.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter							
Pipefitter							
Electrician				x			
Boilermaker							
Sheet metal							
Ironworker							
Pipe welder							
Structural welder							
Equipment Operator				x			
Crane Operator				x			
Millwright							
Instrument fitter							
Supervisors				x			

- **Project No.25**

- There is no data for Question No.13 and 14.

25.17	No Impact	Slight	Moderate	Severe
Cost		x		
Schedule		x		
Safety	x			
Rework		x		

25.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter	x					
Electrician			x			
Boilermaker	x					
Sheet metal	x					
Ironworker	x					
Pipe welder	x					
Structural welder	x					
Equipment Operator	x					
Crane Operator	x					
Millwright	x					
Instrument fitter	x					
Supervisors	x					

25.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter	x						
Electrician		x					
Boilermaker	x						
Sheet metal	x						
Ironworker	x						
Pipe welder	x						
Structural welder	x						
Equipment Operator	x						
Crane Operator	x						
Millwright	x						
Instrument fitter	x						
Supervisors	x						

25.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter		x					
Pipefitter		x					
Electrician			x				
Boilermaker			x				
Sheet metal		x					
Ironworker		x					
Pipe welder		x					
Structural welder		x					
Equipment Operator		x					
Crane Operator		x					
Millwright		x					
Instrument fitter		x					
Supervisors		x					

• Project No.26

26.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter			36	70	23.07	20.37				
Pipefitter				4	27.96	27.96				
Electrician			385	130	23.9	23.9				
Boilermaker			385	216	24.91	24.91				
Sheet metal					23.14	23.14				
Ironworker			30	38	25.09	25.09				
Pipe welder					27.96	27.96				
Structural welder				4	25.09	25.09				
Equipment Operator			36	20	25.9	25.9				
Crane Operator			4	4	26.5	26.5				
Millwright				3	23.99	23.99				
Instrument fitter					27.69	27.69				
Supervisors			8	8	35	35				

• There is no data for Question No.14

26.17	No Impact	Slight	Moderate	Severe
Cost				x
Schedule				x
Safety		x		
Rework				x

26.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter	x					
Electrician			x			
Boilermaker				x		
Sheet metal						x
Ironworker	x					
Pipe welder	x					
Structural welder			x			
Equipment Operator	x					
Crane Operator	x					
Millwright						x
Instrument fitter						x
Supervisors			x			

26.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter			x				
Pipefitter		x					
Electrician			x				
Boilermaker				x			
Sheet metal							x
Ironworker		x					
Pipe welder							x
Structural welder			x				
Equipment Operator	x						
Crane Operator	x						
Millwright							x
Instrument fitter							x
Supervisors				x			

26.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter				x			
Pipefitter	x						
Electrician					x		
Boilermaker			x				
Sheet metal							x
Ironworker			x				
Pipe welder							x
Structural welder			x				
Equipment Operator			x				
Crane Operator				x			
Millwright							x
Instrument fitter							x
Supervisors			x				

- **Project No.27**

27.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter										
Pipefitter					42.21	55.3				
Electrician										
Boilermaker										
Sheet metal										
Ironworker					42.05	49.35				
Pipe welder					43.74	56.03				
Structural welder										
Equipment Operator										
Crane Operator										
Millwright										
Instrument fitter										
Supervisors										

- There is no data for Question No.14

27.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter	x					
Electrician	x					
Boilermaker	x					
Sheet metal	x					
Ironworker	x					
Pipe welder	x					
Structural welder		x				
Equipment Operator	x					
Crane Operator	x					
Millwright	x					
Instrument fitter	x					
Supervisors	x					

27.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter		x					
Electrician	x						
Boilermaker	x						
Sheet metal	x						
Ironworker	x						
Pipe welder		x					
Structural welder		x					
Equipment Operator	x						
Crane Operator	x						
Millwright	x						
Instrument fitter	x						
Supervisors	x						

- There is no data for Question 20.

- **Project No.28**

28.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter	7	14			23.5		50	65	60	100
Pipefitter	8	19			34		50	65	60	100
Electrician										
Boilermaker										
Sheet metal										
Ironworker										
Pipe welder										
Structural welder	4	9			35.5		50	65	60	100
Equipment Operator	2	2			33		50	65	60	100
Crane Operator										
Millwright	5	5			33		50	65	60	100
Instrument fitter										
Supervisors										

28.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	0.15			0
Pipefitter	0.1			0
Electrician				
Boilermaker				
Sheet metal				
Ironworker				
Pipe welder				
Structural welder	0.12			0
Equipment Operator	0			50
Crane Operator				
Millwright	0.2			0
Instrument fitter				
Supervisors				

28.17	No Impact	Slight	Moderate	Severe
Cost				x
Schedule				x
Safety		x		
Rework				x

28.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter		x				
Pipefitter				x		
Electrician						x
Boilermaker						x
Sheet metal						x
Ironworker						x
Pipe welder				x		
Structural welder				x		
Equipment Operator				x		
Crane Operator						x
Millwright				x		
Instrument fitter						x
Supervisors						

| 28.19 | None | To Some Degree | Moderate | Very Much | Almost Completely | All | Not Applicable |
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter			x				
Pipefitter					x		
Electrician							x
Boilermaker							x
Sheet metal							x
Ironworker							x
Pipe welder				x			
Structural welder				x			
Equipment Operator			x				
Crane Operator							x
Millwright				x			
Instrument fitter							x
Supervisors							x

28.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter				x			
Pipefitter			x				
Electrician							
Boilermaker							
Sheet metal							
Ironworker							
Pipe welder			x				
Structural welder			x				
Equipment Operator			x				
Crane Operator							
Millwright			x				
Instrument fitter							
Supervisors				x			

• Project No.29

29.13	Estimated number of hires	Actual number of hires	Estimated number of peak craft	Actual number of peak craft	Estimated hourly wages (raw)	Actual hourly wages (raw)	Estimated per-diem ($)		Actual per-diem ($)	
							Min	Max	Min	Max
Carpenter		14	10	12	32	28.69	60	100	60	100
Pipefitter		85	30	74	29	32.69	60	100	60	100
Electrician		200	70	146	30	30	60	100	60	100
Boilermaker		20	7	13	29.5	30.16	60	100	60	100
Sheet metal		0	0	0	0	0	0	0	0	0
Ironworker		10	4	6	27.5	25.52	60	100	60	100
Pipe welder		60	25	34	40	23.49	60	100	60	100
Structural welder		20	5	12	28.75	31.28	60	100	60	100
Equipment Operator		35	10	21	28.5	26.82	60	100	60	100
Crane Operator		20	5	16	29.5	33.19	60	100	60	100
Millwright		12	5	11	30	29.09	60	100	60	100
Instrument fitter		0	0	0	0	0	0	0	0	0
Supervisors		28	30	26	35	48.84	100	130	100	130

29.14	Voluntary Turnover Rate	Involuntary Turnover Rate	Apprentice to Journeyman Ratio	Percent Certified
Carpenter	0.1	7	n/a	1
Pipefitter	12	3	n/a	1
Electrician	30	7	3;1	1
Boilermaker	45	9	n/a	1
Sheet metal	n/a	n/a	n/a	1
Ironworker	60	7	n/a	1
Pipe welder	70	6	n/a	1
Structural welder	60	7	n/a	1
Equipment Operator	60	7	n/a	1
Crane Operator	25	0	n/a	1
Millwright	9	0	n/a	1
Instrument fitter	n/a	n/a	n/a	n/a
Supervisors	7	1	n/a	1

29.17	No Impact	Slight	Moderate	Severe
Cost				
Schedule				
Safety				
Rework				

29.18	No difficulty	Slight	Moderate	Severe	Very Severe	Not Applicable
Carpenter	x					
Pipefitter	x					
Electrician		x				
Boilermaker	x					
Sheet metal	x					
Ironworker	x					
Pipe welder	x					
Structural welder	x					
Equipment Operator	x					
Crane Operator	x					
Millwright	x					
Instrument fitter						
Supervisors	x					

29.19	None	To Some Degree	Moderate	Very Much	Almost Completely	All	Not Applicable
	0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%	
Carpenter	x						
Pipefitter		x					
Electrician			x				
Boilermaker		x					
Sheet metal							
Ironworker	x						
Pipe welder		x					
Structural welder		x					
Equipment Operator	x						
Crane Operator	x						
Millwright	x						
Instrument fitter							
Supervisors		x					

29.20	Do not know	None	Minor Amount	Fair Amount	Moderate Amount	Almost Completely	All
		0%	<25%	25 to less than 50%	50 to less than 75%	75 to less than 100%	100%
Carpenter						x	
Pipefitter				x			
Electrician					x		
Boilermaker					x		
Sheet metal							
Ironworker					x		
Pipe welder				x			
Structural welder							x
Equipment Operator			x				
Crane Operator			x				
Millwright						x	
Instrument fitter							
Supervisors				x			

APPENDIX D

Preliminary Statistical Analysis

1. Sampled Project Demographics

RT-318 Survey Tool

The RT-318 Survey Tool was developed by CII Research Team 318 to collect the demographic data of the construction projects completed in the U.S. and Canada. The total responses to the survey were 29 projects with 26 projects from the U.S. and three from Canada. Figure 1 shows the location of these projects in North America.

Figure 1. Location of RT-318 survey projects in North America

Most projects were performed between 2012 and 2014. However, the largest project in terms of Time and Cost, project No.18, was performed between 2007 and 2012. Most of projects are Heavy Industrial projects (19 out of 29) in the fields of Oil Refining, Chemical and Electrical. The other projects are Building, Light industrial or Infrastructure. Craft workforce in 17 projects were open shop, 7 projects union and 4 ones used both options. The Figure 2 illustrates the Actual Duration of projects and Table 1 shows the Average, Median, Minimum and Maximum of Time and Cost of these projects.
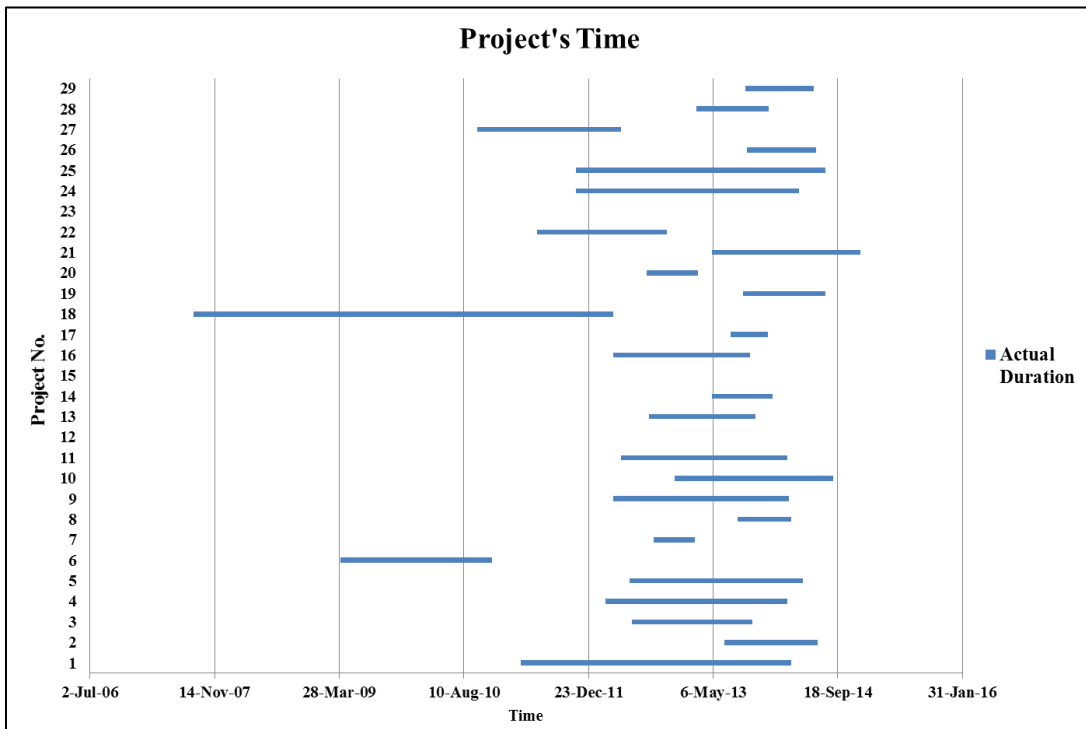
Figure 1. Actual Time of RT-318 Survey Projects

Table 1. Actual Cost and Time of the RT-318 Survey Projects

	Average (Median)	Min, Max
Total actual construction phase cost ($M)	455.15 (45)	3.6, 8549
Actual duration of project (Day)	554.65 (533)	134, 1648

CII Benchmarking and Metrics Database

The CII Benchmarking & Metrics database is the comprehensive database of construction projects performed in the US and Canada. RT-318 received a data file consisting of total 68 projects which 59 of them were performed in the US and 9 projects were performed in Canada. 31 projects (45%) were Heavy Industry projects, 24 projects (35%) were Building and the others were Light Industrial or Infrastructure projects (20%). Figure 3 shows the Actual Duration of these projects.
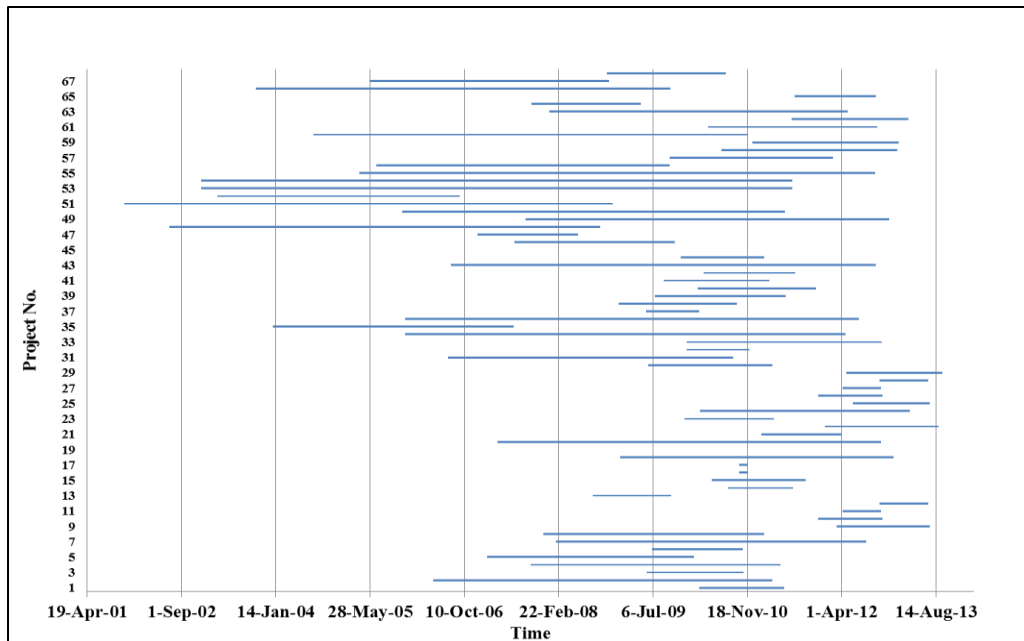
Figure 3. Actual Time of the CII BM&M projects

Table 2 shows the Actual Cost and Actual Schedule information of these projects.

Table 2 Actual Cost and Time of the CII BM&M projects

	Average, (Median)	Min, Max
Total actual construction phase cost ($M)	142.49, (40.1)	0.5, 1799.3
Actual duration of project (Day)	1054.48, (678)	46, 3131

RT-318 Research Database (CII Benchmarking & Metrics and RT-318 Survey):

Our research database was assembled by combining the RT-318 Survey projects and the CII Benchmarking and Metrics projects with the total of 97 construction projects. Of these 97 projects, 85 projects were performed in the U.S. (87%) and 12 were performed in the Canada (12%). All projects were constructed between 2001 and 2014. Figure 4 shows the Actual Duration and Table 3 shows the information about Actual Cost and Actual Time of these aggregated database.
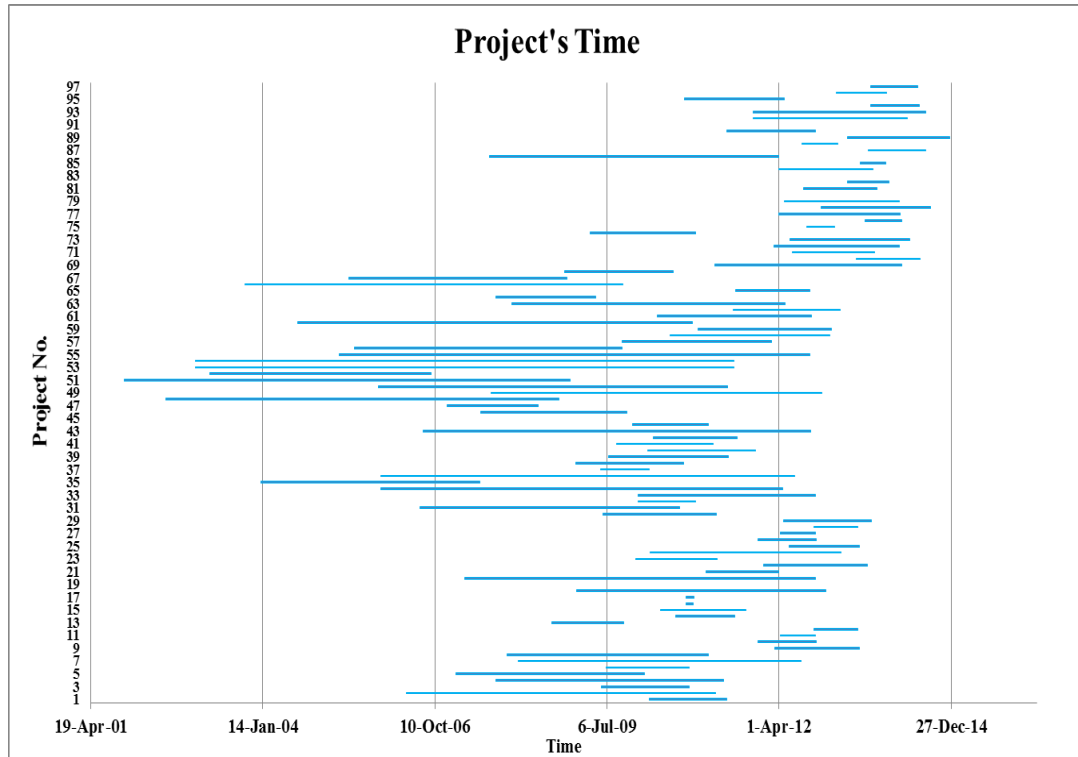
Figure 4. Actual Duration of Research Database projects (CII BM&M and RT-318 Survey)

Table 3. Actual Cost and Time of CII BM&M and RT-318 Survey Projects

(Research Database Projects)

	Average, (Median)	Min, Max
Total actual construction phase cost ($M)	231.3 (40.8)	0.5, 8549
Actual duration of project (Day)	913.2 (622.5)	46, 3131

Figures 5-7 show the Actual Cost Distribution of all projects. Project No.95, the biggest project in term of cost, is shown in another scale in Figure 5 to show all other projects' cost in proper scale. Since there are two projects which their actual cost is not available, the total number of projects shown in this figure is 95. Figure 8 and 9 show the Actual Duration

Distribution of all projects. The total number of projects with available data of Actual Time is 92.
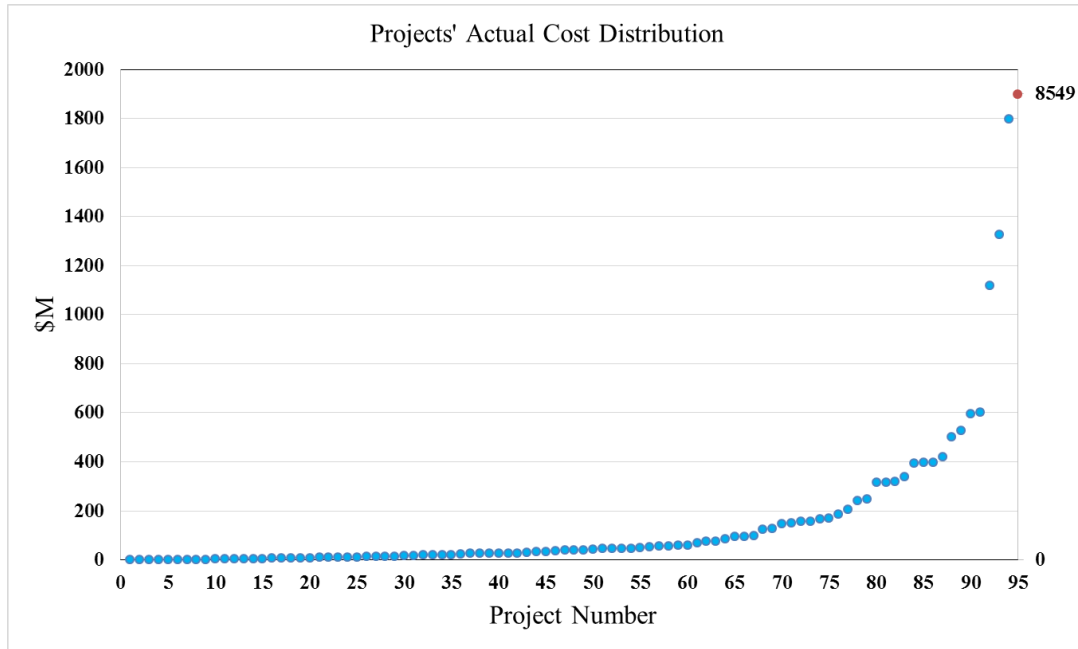
Figure 5. Actual Cost Distribution of Research Database Projects

(CII BM&M and RT-318 Survey)
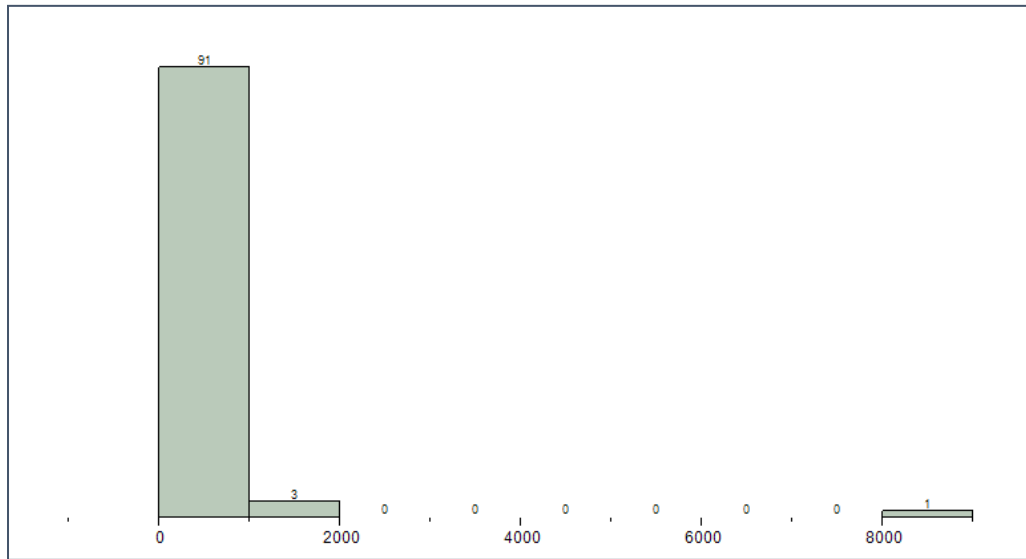
Figure 6. Actual Cost Distribution of Research Database Projects ($M)

(CII BM&M and RT-318 Survey)
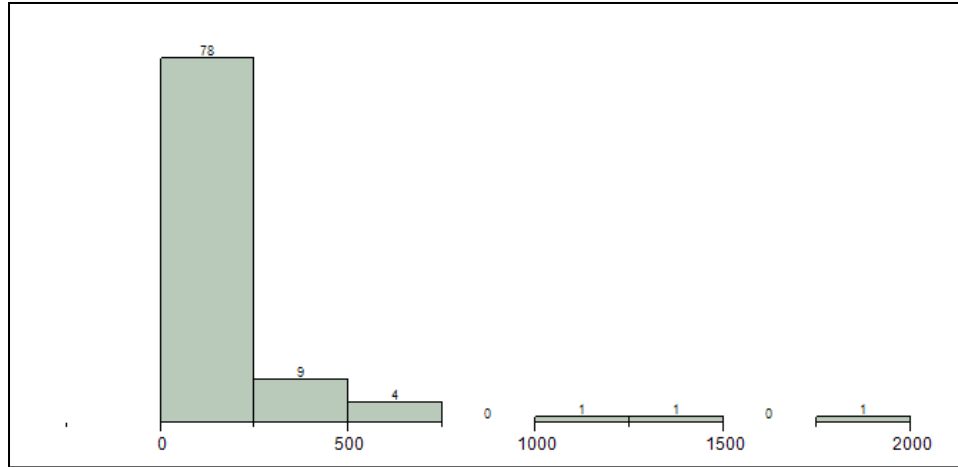
Figure 7. Actual Cost Distribution of Research Database Projects ($M)

(CII BM&M and RT-318 Survey, Project No.95 Excluded)
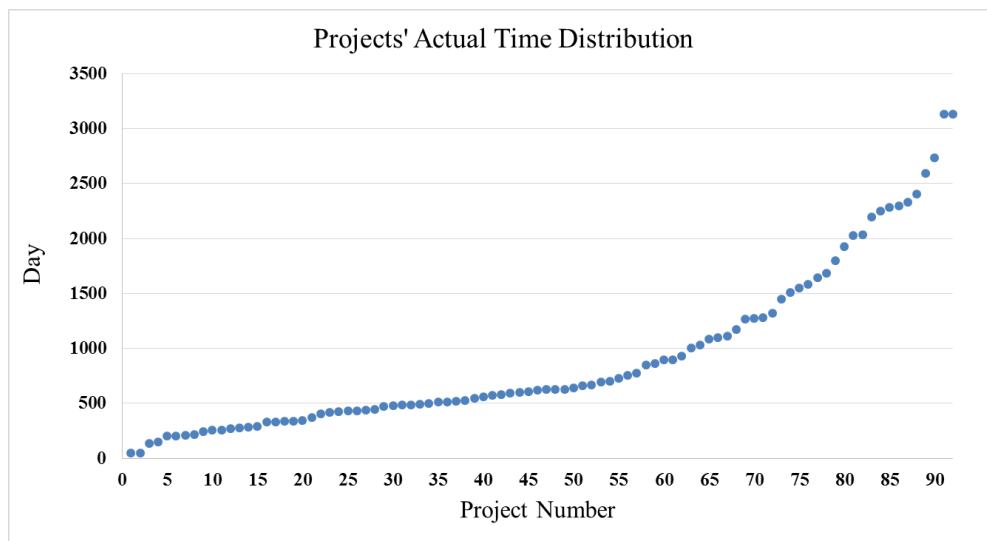
Figure 8. Actual Duration Distribution of Research Database Projects

(CII BM&M and RT-318 Survey)
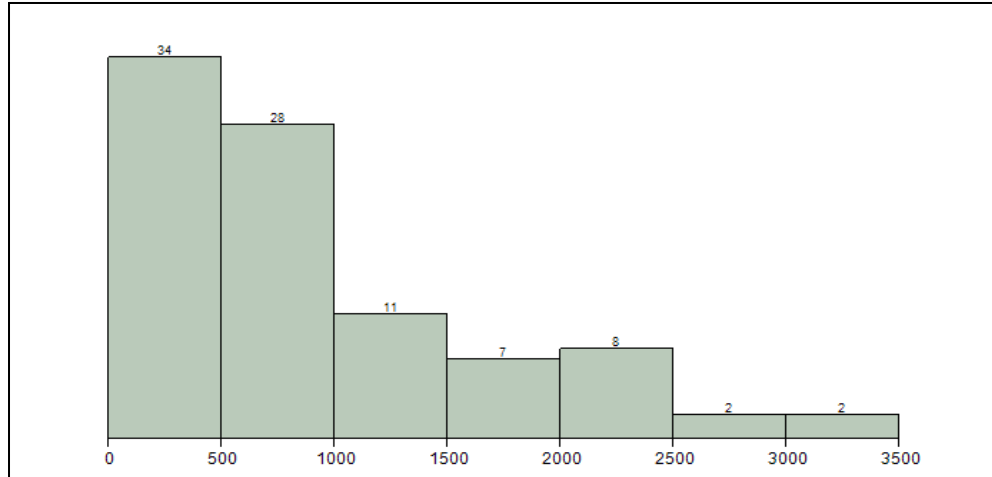
Fig 9. Actual Duration Distribution of Research Database Projects (Day)

(CII BM&M and RT-318 Survey)

2. RT-318 Survey projects workforce data analysis

Staffing Difficulties by Trade (RT-318 Survey Projects)

Question No.18 in RT-318 Survey asked respondents to indicate the level of impact staffing difficulties they experienced on their project among 13 trades. The respondents required to choose the difficulty level from No difficulty, Slight, Moderate, Severe, and Very Severe. The Figure 10 shows the number of projects in each level of staffing difficulty by trade.
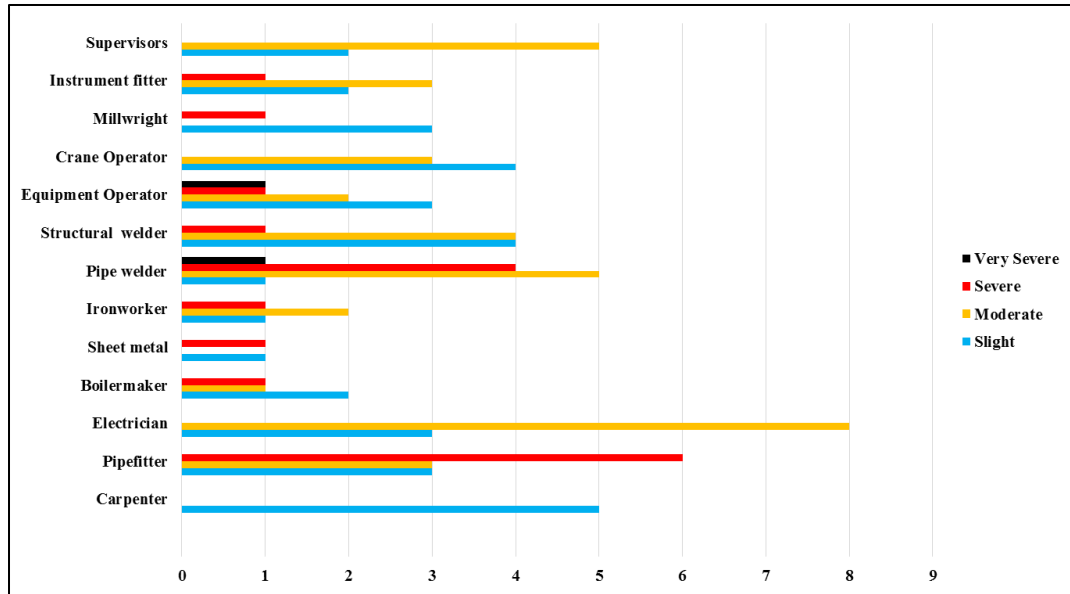
Fig 10. Number of Project in each Staffing Difficulties level by Trade (RT-318 Survey Projects)

If we weight five levels of staffing difficulties as follow: No difficulty=0, Slight =1, Moderate= 2, Severe = 3 and Very Severe=4 and then multiply them to the number of projects in each trade, we can find the trades with highest and lowest level of staffing difficulty among RT-318 Survey projects. The Table 4 shows the score of staffing difficulty for each trade.

Table 4. The Score of Staffing Difficulty for each Trade (RT-318 Survey projects)

Trade	Staffing Difficulty Score
Pipe welder	43.88
Pipefitter	33.43
Structural welder	30.00
Electrician	26.00
Instrument fitter	22.00
Equipment Operator	19.16
Boilermaker	16.55
Supervisors	16.42
Crane Operator	14.44
Ironworker	10.40
Millwright	9.75
Sheet metal	8.67
Carpenter	6.50

The result shows that Pipe welder, Pipefitter, Structural welder, and Electrician have the highest difficulty staffing among other trades. Sheet metal and Carpenter have the lowest staffing difficulty in these 13 trades.

Less Skilled and/or Experienced Hiring by Trade (RT-318 Survey Projects)

In the Question No.19, the RT-318 Survey asked respondents to indicate the percentage of the total hire involved personnel with less skill and/or experience than expected among 13 trades. The Figure 11 shows the number of projects in each level by trade.
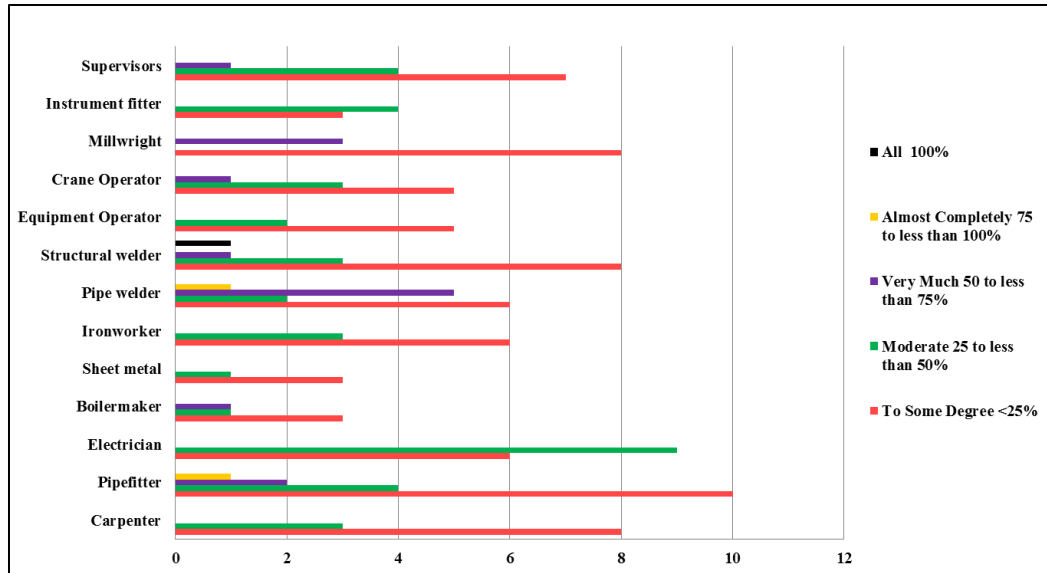
Figure 11. Number of projects in each level of percentage of the total hire involved personnel with less skill and/or experience than expected (RT-318 Survey Projects)

If we weight five levels of percentage of the total hire involved less skilled and/or experienced personnel as follow: None (0%) =0, To Some Degree (<25%) =1, Moderate (25 to less than 50%) =2, Very Much (50 to less than 75%) =3, Almost Completely (75 to less than 100%) = 4, and All (100%) = 5 and then multiply them to the number of projects for each trade, we can find the trades with highest and lowest percentage of involving less skilled or experienced hiring among RT-318 Survey projects. The Table 5 shows the result of this analysis

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Table 5. The Score of Trade involving less skilled or experienced hiring (RT-318 Survey projects)

Trade	Less Skilled or Experienced Hiring Score
Pipe welder	42.65
Structural welder	36.67
Pipefitter	33.33
Electrician	28.57
Millwright	23.61
Supervisors	22.50
Instrument fitter	21.15
Crane Operator	18.42
Carpenter	17.50
Boilermaker	15.38
Ironworker	15.00
Equipment Operator	12.50
Sheet metal	10.42

The result shows that Pipe welder, Structural welder, Pipefitter, and Electrician have highest involvement of hiring less experienced or skilled personnel among all 13 trades and Equipment Operator and Sheet metal are those trades with lowest involvement of hiring less experienced or skilled personnel.

Team Hiring by Trade (RT-318 Survey Projects)

In Question No.20 of RT-318 Survey, the respondents were required to indicate the

percentage of total hires involved Team Hiring in each trade. The Figure 12 shows the number of projects in each level by trade.
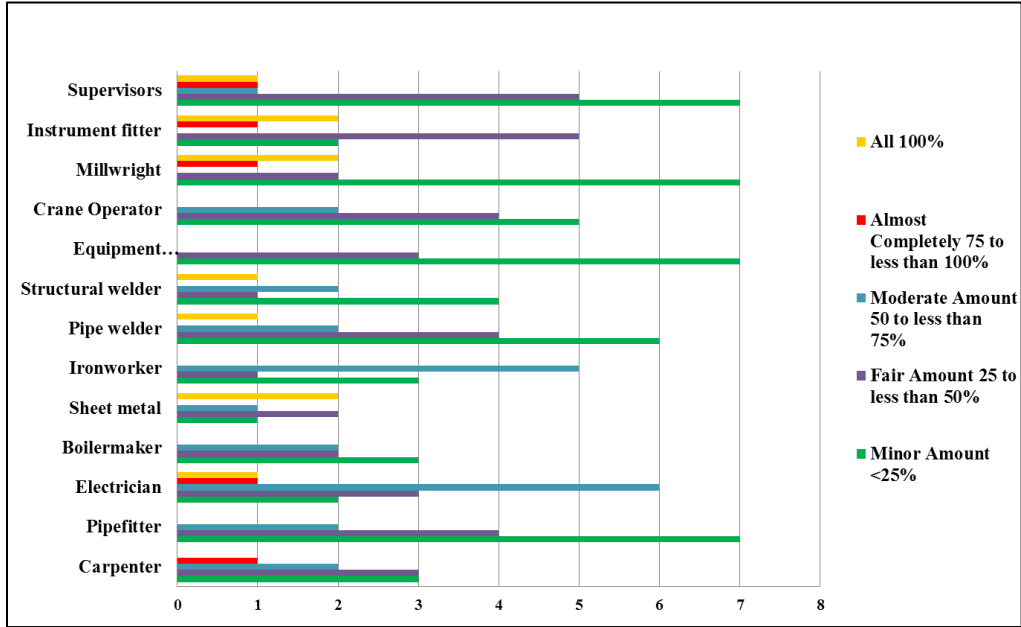
Fig 12. Number of projects in each level of percentage of Team Hiring by Trade (RT-318 Survey Projects)

If we weight five levels of percentage of the Team Hiring as follow: None (0%) =0, Minor Amount (<25%) =1, Fair Amount (25 to less than 50%) =2, Moderate Amount (50 to less than 75%) =3, Almost Completely (75 to less than 100%)=4, and All (100%) =5 and then multiply them to the number of projects in each trade, we find trades with the highest and lowest percentage of Team Hiring among RT-318 Survey projects. The Table 6 shows the result of this analysis.

Table 6. Score of Trade Team Hiring (RT-318 Survey projects)

Trade	Team Hiring Score
Electrician	42.00
Ironworker	35.00
Boilermaker	34.13
Supervisors	29.65
Carpenter	28.50
Crane Operator	28.50
Pipe welder	28.00
Instrument fitter	28.00
Pipefitter	25.94
Structural welder	22.91
Millwright	22.50
Sheet metal	21.00
Equipment Operator	19.50

Electrician, Ironworker, and Boilermaker are trades with the highest involvement in Team Hiring among all 13 trades in RT-318 Survey projects and Sheet metal and Equipment Operator are those trades with lowest involvement of Team Hiring.

Hourly Wages Increase by Trade (RT-318 Survey projects)

In Question No.13 of RT-318 Survey, the respondents were asked to provide information of Estimated and Actual Hourly Wage in each trade. Therefore, we can calculate the

percentage of change of hourly wage in each trade. The Table 7 shows the average of hourly wage change in all projects in each trade.

Table 7. Average Percent Change of Estimated Hourly Wages to Actual Hourly Wages (RT-318 Survey Projects)

Trades	Average % of Change of Estimated hourly wages to Actual hourly wages (%)[1]
Pipefitter	5.89
Supervisors	4.27
Ironworker	3.91
Structural welder	3.88
Boilermaker	3.07
Pipe welder	1.74
Instrument fitter	1.24
Electrician	0.75
Sheet metal	-0.16
Crane Operator	-0.78
Millwright	-1.08
Carpenter	-1.42
Equipment Operator	-4.46
Total Average	**1.30**

The result of analysis shows that Pipefitter, Supervisors, Ironworker, Structural welder and Boilermaker have the highest percent of hourly wage change, more than 3%, comparing to

other trades. Sheet metal, Crane Operator, Millwright, Carpenter, and Equipment Operator are those trades that the actual hourly wage is less than estimated one.

Discussion and Conclusion

The analysis of workforce information of RT-318 Survey projects shows that currently the Pipe welder, Pipefitter, Structural welder, and Electrician are those trades with the highest level of staffing difficulty. Interestingly, these trades also are the four top trades with involvement of hiring less experienced or skilled personnel among all 13 trades. Among these trades, the Pipefitters and Structural welders are among four top trades with the highest percentage of hourly wage change with more than 3% increase compared to planned wage. The Supervisor, Ironworker, and Boilermaker also are the trades which have more than 3% increase in hourly wage.

On the other hand, Carpenter, Sheet metal, Millwright, and Ironworker are those trades with lowest staffing difficulty. Among these trades, Sheet metal and Iron worker and Carpenter also are among trades with lowest involvement of hiring less experienced or skilled personnel. Interestingly, Carpenter, Millwright and Sheet metal are among five trades which their actual hourly wage is less than estimated one.

In conclusion, it can be stated that trades with the highest level of staffing difficulty have higher level of hiring less experienced or skilled personnel and higher increase in actual wage comparing to estimated one. On the other hand, trades with lower staffing difficulty have lower level of hiring less experienced or skilled personnel and lower increase in actual wage comparing to estimated one. This shows the impact of craft labor staffing difficulty on hiring of less experienced or skilled personnel and increase in their hourly wage.

3. Craft Labor Shortage Measurement

In order to find the impact of skilled labor shortage on project performances, first of all, we need to measure the level of shortage in projects and then identify the relationship between craft labor shortage and project performance. In RT-318 Survey, there are three questions designed to find the impact of labor shortage on project. Question No.16 asks respondents whether a workforce shortage impacted their project's performance or not. Question No.17 asks about the level of this negative impact on four performance parameters of Cost, Schedule, Safety and Rework. The levels are No Impact, Slight, Moderate, and Severe. Question No.18 requires the respondents to indicate the level of impact staffing difficulties had on the project in each 13 trades. There are five levels defined for this impact which are No difficulty, Slight, Moderate, Severe, Very Severe. To use this variable in our analysis, we assigned score to each level. The Table 8 shows these levels, definition as described in RT-318 Survey and assigned scores.

Table 8. Levels of impact of staffing difficulties in RT-318 Survey projects

Level	Definition	Score
No difficulty	There was no shortage. Able to staff the project with no delay on construction	0
Slight	Staffing difficulties led to consumption of schedule float and/or contingency	1
Moderate	Staffing difficulties led to delay of completing project activities on time	2
Severe	Staffing difficulties led to delay of completing project milestones	3
Very Severe	Staffing difficulties led to project delay	4

In the next step, we calculate the average of staffing difficulty of these 13 trades for each project. The following is the equation used for this calculation:

Staffing Difficulty for Project = [(0×A) + (1×B) + (2×C) + (3×D) + (4×E)] / (A+B+C+D+E)

in which:

A= Number of trades with No staffing difficulty

B= Number of trades with Slight staffing difficulty

C= Number of trades with Moderate staffing difficulty

D= Number of trades with Severe staffing difficulty

E= Number of trades with Very Severe staffing difficulty

In the CII BM&M database section No.9, the respondents indicated the impact of Availability of Skilled Labor comparing to what has been planned in the planning stage of their projects. The level can be from Extremely Negative (-5) to Extremely Positive (+5) and Zero indicates "As Planned" situation. Since we have two different scales of measurement about craft labor availability in our two databases, we need to merge them to one scale measurement to be able use them together for our analysis. Therefore, we decided to convert CII BM&M score scale to the RT-318 one.

Any number between zero (As Planned) to +5 (Extremely Positive) would be converted to No difficulty (0) defined in RT-318 Survey. This conversion is based on the assumption that projects with score in this range was not impacted by shortage of craft workers. The BM&M questionnaire defined score=0 as the situation of the original plan and score>0 as

the condition that the availability of craft worker has positive impact on project performance. Therefore, it can be concluded that score ≥0 is the condition that the project has at least no staffing difficulty.

The other score between -5 (Extremely Negative) to -1 would be scaled proportionally to the number between 1 (Slight) to 4 (Very Severe) defined in RT-318 Survey. This can be done by multiplying any score between -1 and -5 to (-4/5). Then they will be converted to the scores between 1 to 4 defined in RT-318 Survey. The Figure No.13 illustrates this process of scale converting.
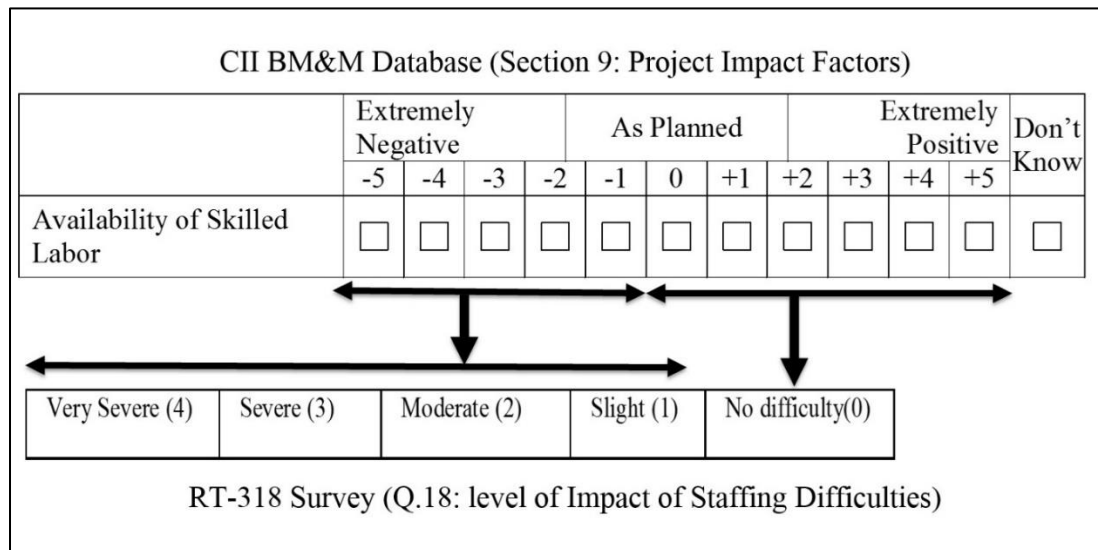
Figure No 13. The Conversion of CII BM&M scale of Availability of Skilled Labor to RT-318 Scale

4. Constructing Research Database: Combining CII Benchmarking & Metrics and RT-318 Survey databases

Romeu (2004) argues combining data sets should only be done when there is no large statistical difference between associated distributions and their parameters. He proposes the following implementation procedure for combing data sets:

- Perform an Explanatory Data Analysis

- Perform graphical analysis

- Perform goodness of fit analysis

- Perform analysis of variance

- Perform regression analysis

- Quantify statistical difference

Therefore, we perform these tests on these two datasets to make sure there is no significant difference between them. Since we want to conduct the regression analysis on Cost Change, Schedule Change and TRIR, we also perform these diagnostic tests on these three variables.

The first and second analysis can be done in any data with any type of distribution. The other tests such as comparing means and variances can be done when the distribution of the datasets is normal. Since all five variables in both two databases are far from to be considered as a normal distribution, we choose a distribution-free rank sum test, Mann-Whitney test, which is considered a powerful test for comparing two datasets when they are not normally distributed.

The Mann-Whitney Test also known as Mann–Whitney–Wilcoxon (MWW) is the Non-Parametric Distribution-Free Rank Sum Test that test the null hypothesis of no treatment effect between two independent samples against an alternative hypothesis (Hollander et all, 2014). The null hypothesis is:

$$Ho: F(t) = G(t) \quad \text{for every t} \qquad \text{or}$$

Ho: The distribution of scores for two groups are equal

F: Distribution of sample 1 (X), G: Distribution of sample 2 (Y)

It should be noted that the null hypothesis assumes that the X variable and Y variable have the same probability distribution but the distribution is not specified (Hollander et all, 2014).

The alternative hypothesis is that the Y is not equal to X.

$$\text{Ha: G (t) = F (t+}\Delta\text{)} \quad \text{for every t} \qquad \text{and} \qquad \Delta \neq 0 \qquad \text{or}$$

Ha: The distribution of scores for sample 2 (Y) is not equal to sample 1(X)   or

Ha: The mean rank in sample 2 (Y) is not equal to mean rank in sample 1 (X)   or

Ha: the distribution for X and Y have the same shape but the one for Y is shifted up or shifted down compared to the one for X (Agresti and Finlay, 2009)

Hollander et all (2014) mentioned the assumptions of Mann-Whitney Test as:

1) The observations in both samples are random and independent from each other

2) The variables are Quantitative Continues variable

For all following variables in both datasets in this section, both assumptions are satisfied. The software used for performing tests is SPSS 22. The significance level (α) for all tests is 0.05.

Comparison of Actual Cost of CII BM&M and RT-318 Survey datasets:

The Figures 14 & 15 and Table 9 & 10 shows the Actual Cost Distribution and Summary Statistics for both two datasets. As illustrated, both datasets have similar and non-normal distributions.
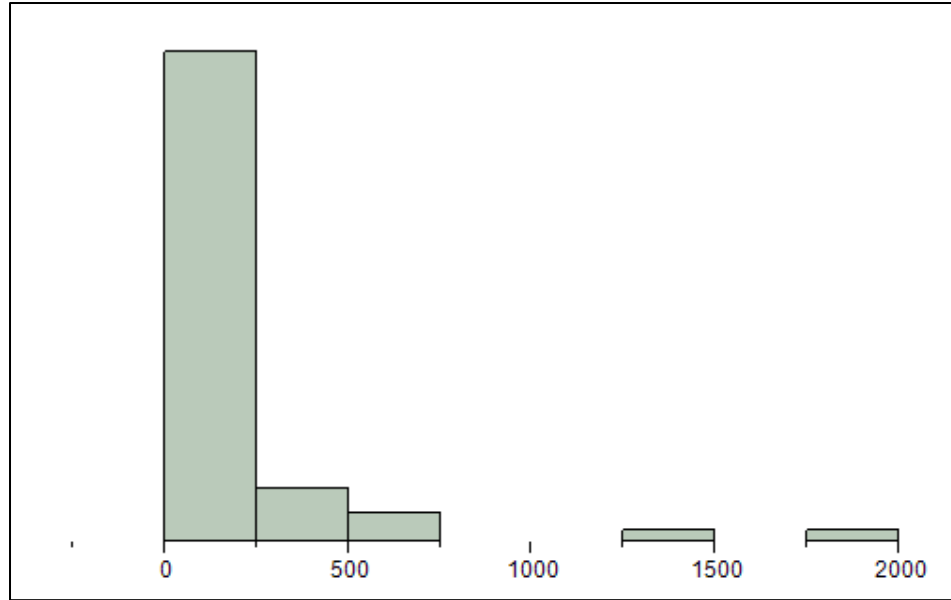
Figure 4.14. CII BM&M Actual Cost Distribution

Table 4.9. Summary Statistics Actual Cost CII BM&M Projects

Mean	142.48
Std Dev	290.09
Std Err Mean	35.17
N	68
Median	40.05
Range	1798.8
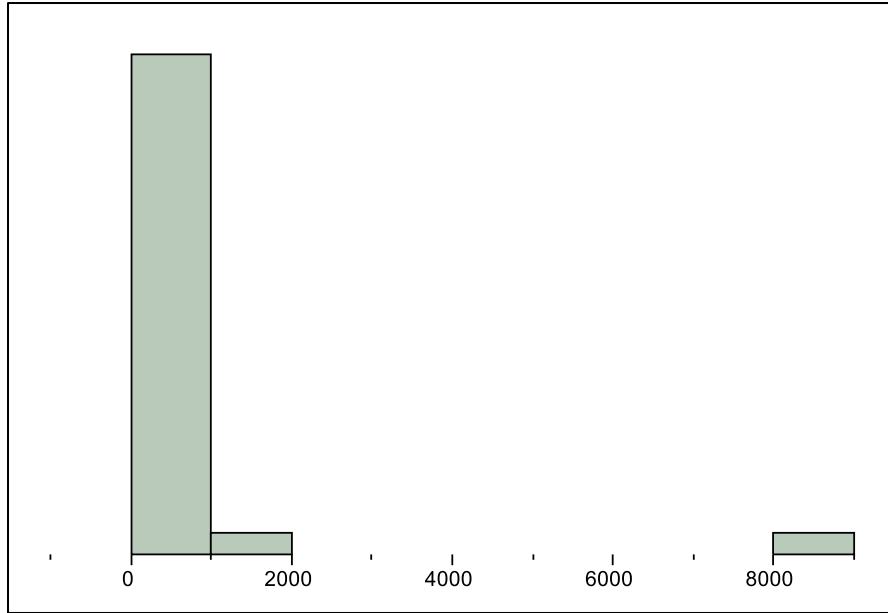
Figure 15. RT-318 Survey Projects Actual Cost Distribution

Table 10. Summary Statistics Actual Cost RT-318 Survey Projects

Mean	455.14
Std Dev	1635.31
Std Err Mean	314.71
N	27
Median	45
Range	8545.4

As discussed before, the Mann-Whitney Test is an appropriate test to check whether two datasets with similar distribution have significant difference or not. The Table 11 shows the results of this test for comparing Actual Cost Distribution in our two datasets. The two-tailed p-value is 0.367 which means we cannot reject the null hypothesis. Therefore, we can state that there is no statistically significant difference between Actual Cost of these two datasets.
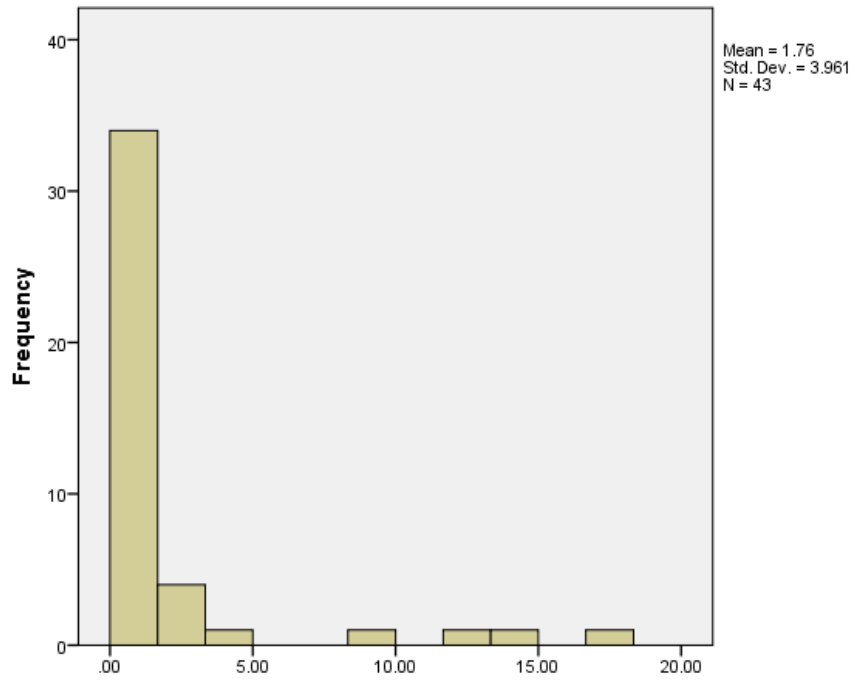
Table 11. Mann-Whitney Test for comparing Actual Cost of BM&M and RT-318 Projects

	VAR01	N	Mean Rank	Sum of Ranks
	Ranks			
	0.00	68	46.38	3154.00
Actual Cost	1.00	27	52.07	1406.00
	Total	95		

Test Statistics[a]

	Actual Cost
Mann-Whitney U	808.000
Wilcoxon W	3154.000
Z	-0.908
Asymp. Sig. (2-tailed)	0.364
Exact Sig. (2-tailed)	0.367
Exact Sig. (1-tailed)	0.184
Point Probability	.001
a. Grouping Variable: VAR01	

Comparison of Actual Time of CII BM&M and RT-318 Survey datasets:

The Figures 16 & 17 and Table 12 & 13 shows the Actual Time Distribution and Summary Statistics for both two datasets. As illustrated, the Actual Time Distribution of RT-318 Survey Projects is close to normal distribution but the Actual Time Distribution of CII BM&M projects is highly righ skewed. Since these two datasets do not have similar distribution, we cannot perform the Mann-Whitney Test to compare them as this test assumes both datasets have similar shape distribution. However, the median in both datasets is close to each other, 678 comparing to 533.
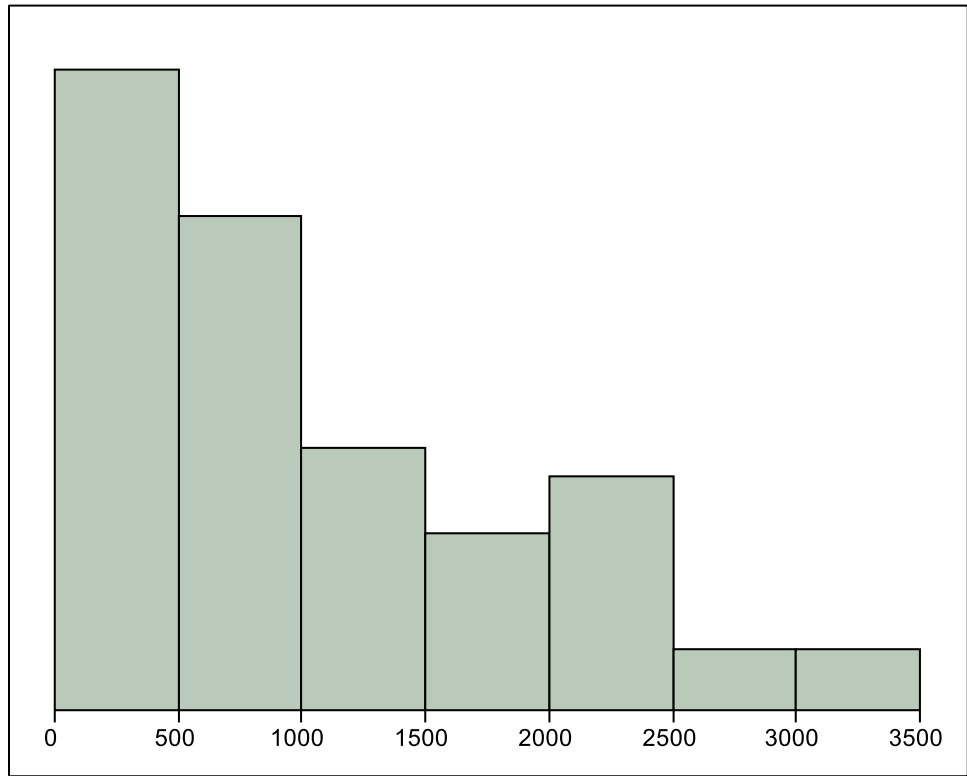
Figure 16. CII BM&M Projects Actual Time Distribution

Table 12. Summary Statistics Actual Time CII BM&M Projects

Mean	1054.48
Std Dev	802.56
Std Err Mean	98.78
N	66
Median	678
Range	3085
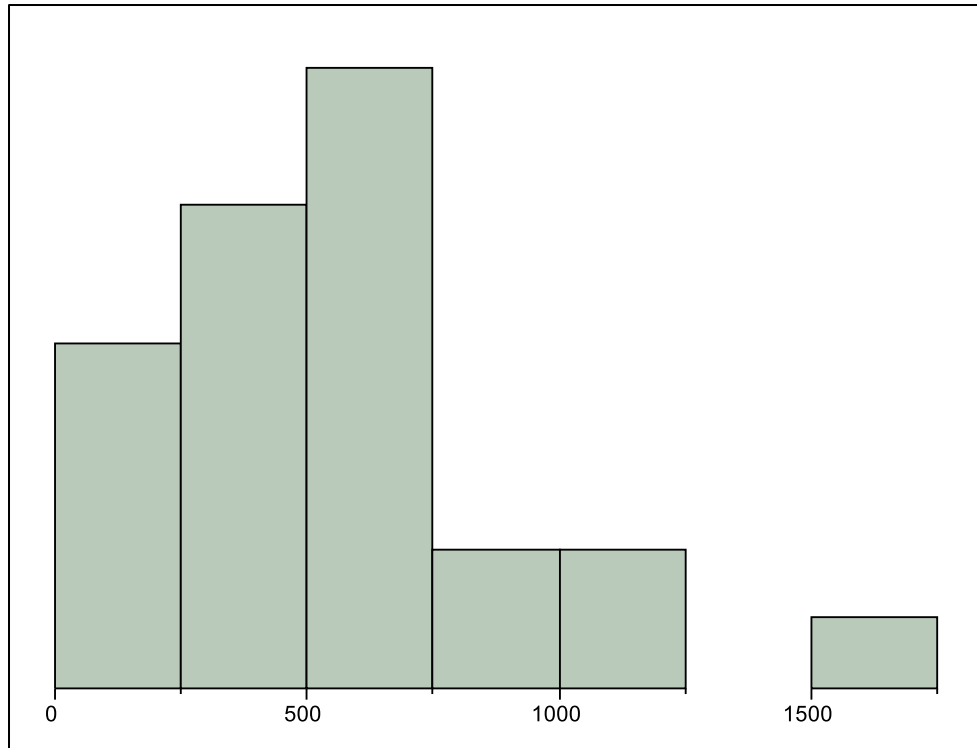
Figure 17. RT-318 Survey Projects Actual Time Distribution

Table 13. Summary Statistics Actual Time of RT-318 Survey Projects

Mean	554.61
Std Dev	346.17
Std Err Mean	67.89
N	26
Median	533
Range	1550

Comparison of Actual Cost Change of CII BM&M and RT-318 Survey datasets

The Figures 18 and 19 show the Distribution, Total number, Mean and Standard Devation for Actual Cost Change of both datasets. As illustrated, both data sets have similar shape and non-normal distribution. Therefore, we can perform a Mann-Whitney Test to compare their distributions. Table 14 shows the result of this test. The two-tailed p-value of the test

is 0.091 which means we cannot reject the null hypothesis. Therefore, we can state that there is no significant difference between these two distributions.

Mean = 6.77
Std. Dev. = 40.502
N = 70
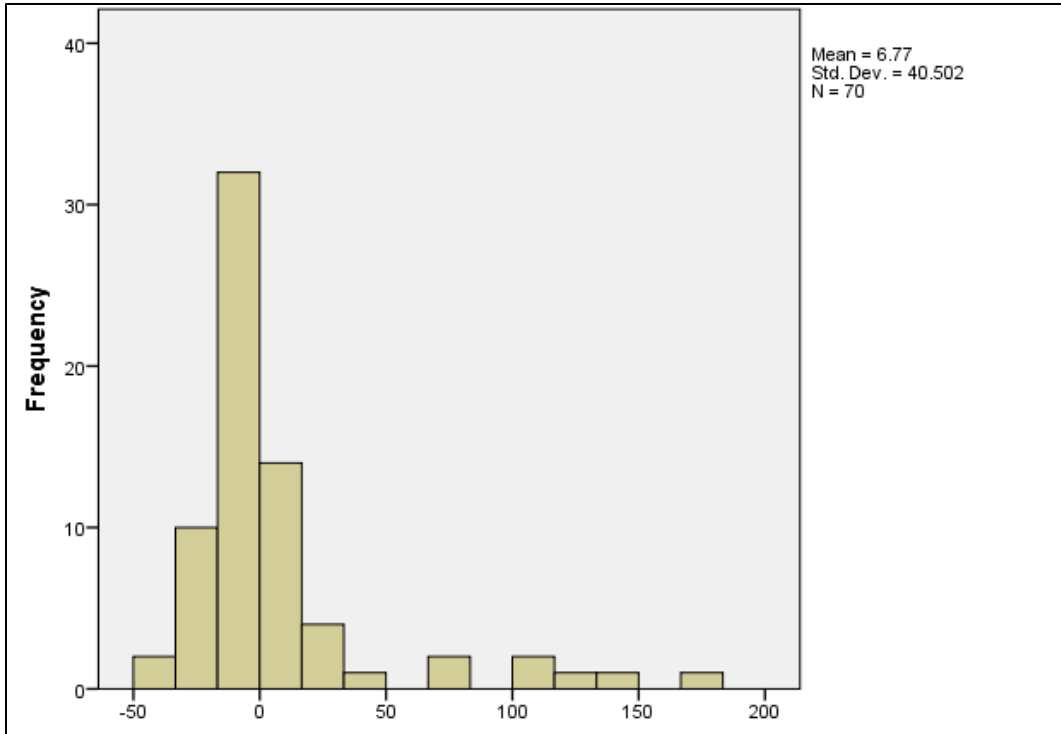
Figure 18. Actual Cost Change of CII BM&M projects

Mean = 11.83
Std. Dev. = 42.497
N = 22
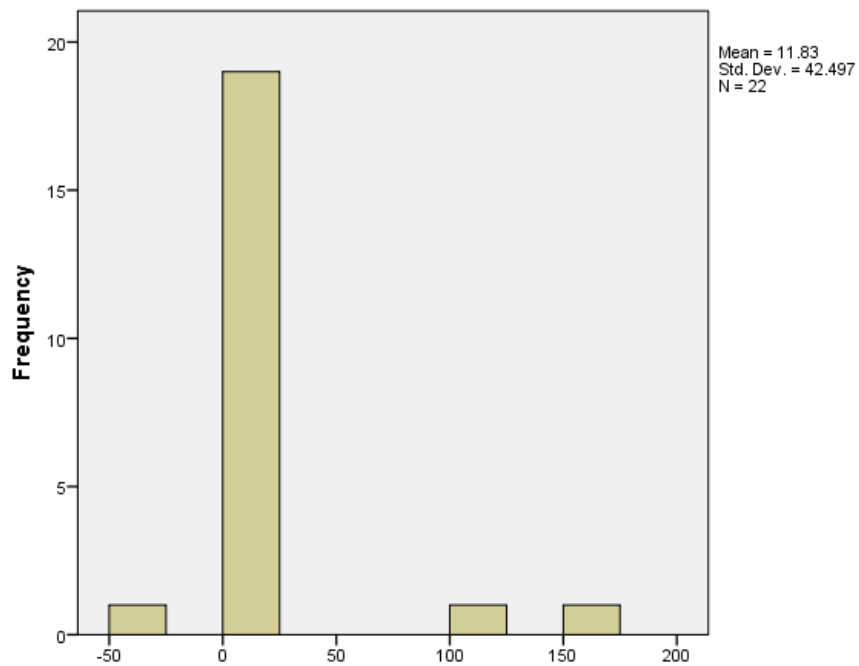
Figure 19. Actual Cost Change of the RT-318 projects

Table 14. Mann-Whitney Test for comparing Actual Cost of BM&M and RT-318 Projects

	V3	N	Mean Rank	Sum of Ranks
			Ranks	
	0.0	70	43.86	3070.00
Y	1.0	22	54.91	1208.00
	Total	92		

Test Statistics	
	Y
Mann-Whitney U	585.000
Wilcoxon W	3070.000
Z	-1.693
Asymp. Sig. (2-tailed)	.090
Exact Sig. (2-tailed)	0.091
Exact Sig. (1-tailed)	.045
Point Probability	.000
a. Grouping Variable: V3	

Comparison of Actual Time Change of CII BM&M and RT-318 Survey datasets

The Figures 20 and 21 show the Distribution, Total number, Mean and Standand Devation of Actual Time Change for both two datasets. As illustrated, both datasets have similar non-normal distributions. Therefore, we can perform a Mann-Whitney Test to compare two distributions. Table 15 shows the result of this test. The two-tailed p-value is 0.24 which means we cannot reject the null hypothesis. Therefore, we can state that there is no significant difference between these two distributions.
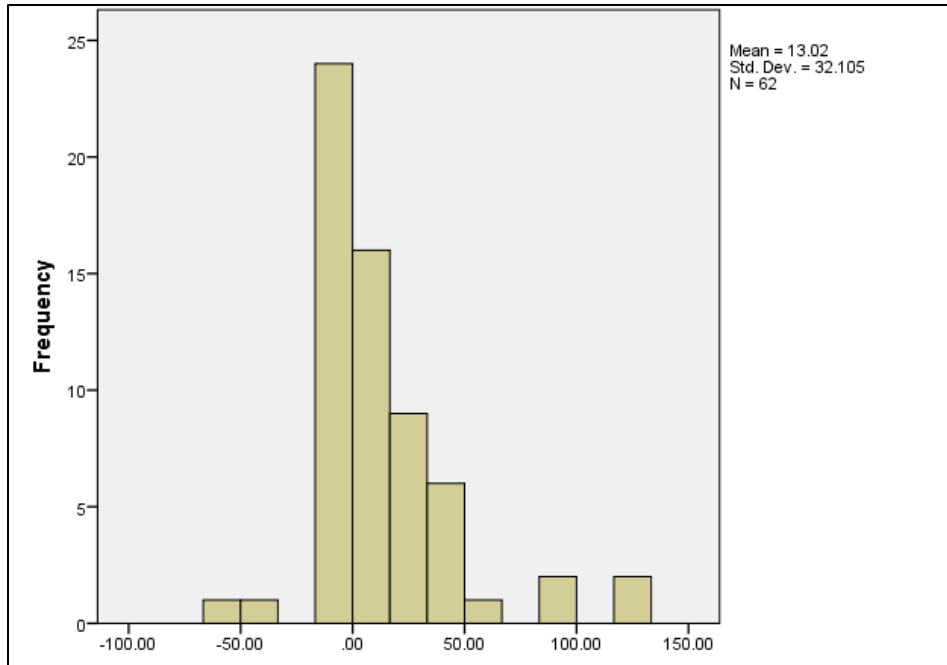
Figure 20. Actual Time Change of CII BM&M projects
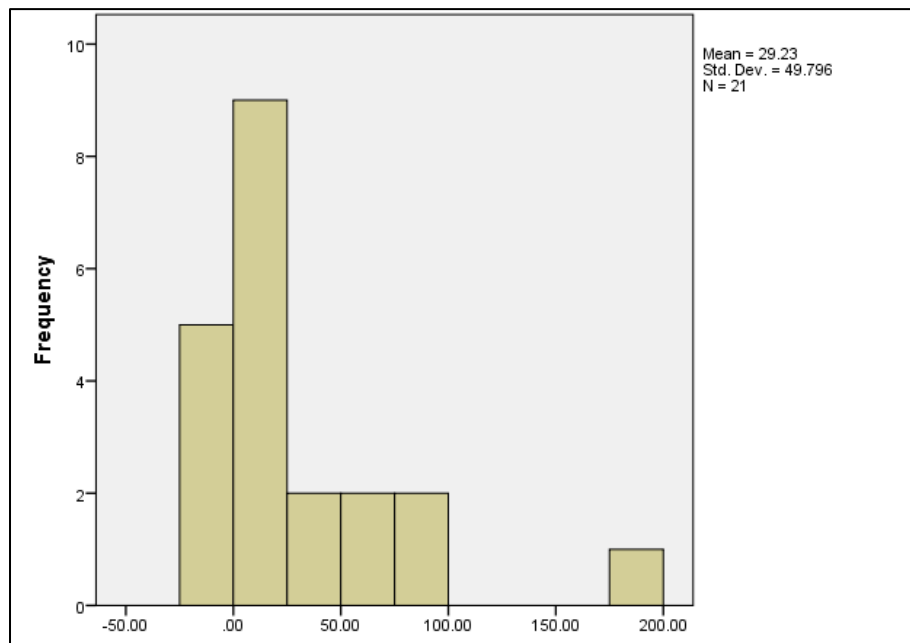
Figure 21. Actual Time Change of the RT-318 projects

Table 15. Mann-Whitney Test for comparing Actual Time of BM&M and RT-318 Projects

	V3	N	Mean Rank	Sum of Ranks
	Ranks			
	0	62	40.19	2491.50
Y	1	21	47.36	994.50
	Total	83		

Test Statistics	
	Y
Mann-Whitney U	538.500
Wilcoxon W	2491.500
Z	-1.179
Asymp. Sig. (2-tailed)	.238
Exact Sig. (2-tailed)	<u>0.241</u>
Exact Sig. (1-tailed)	.121
Point Probability	.001
a. Grouping Variable: V3	

Comparison of Safety Performance (TRIR) of CII BM&M and RT-318 Survey datasets

The Figures 22 and 23 show the Distribution, Total Number, Mean and Standard Devation of TRIR for both datasets. As illustrated, both data sets have similar non-normal distributions. Therefore, we can perform a Mann-Whitney Test to compare their distributions. The result of test is shown in Table 16. The two-tailed p-value is 0.3 which means we cannot reject the null hypothesis. Therefore, we can state that there is no significant difference between these two distributions.

Figure 22. TRIR of CII BM&M projects
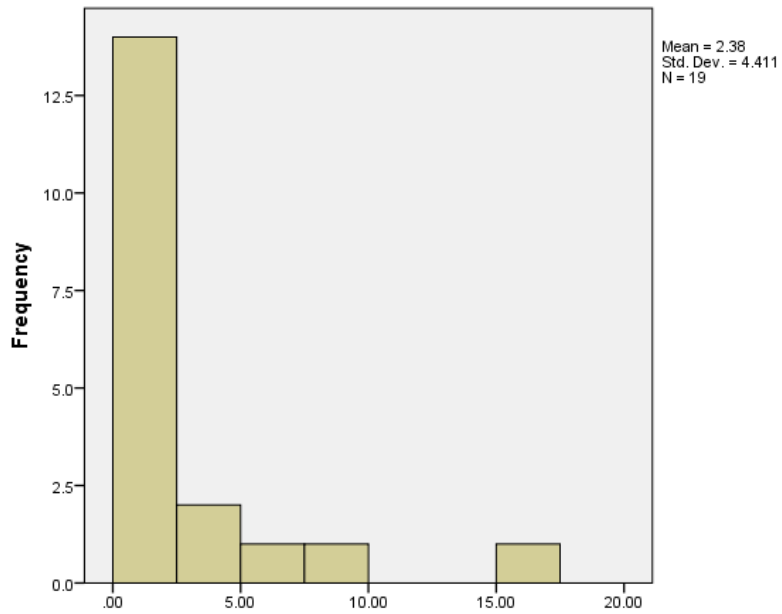
Figure 23. TRIR of the RT-318 projects

Table 16. Mann-Whitney Test for comparing TRIR of BM&M and RT-318 Projects

	V3	N	Mean Rank	Sum of Ranks
			Ranks	
y	0	43	30.02	1291.00
	1	19	34.84	662.00
	Total	62		

Test Statistics[a]	
	y
Mann-Whitney U	345.000
Wilcoxon W	1291.000
Z	-1.044
Asymp. Sig. (2-tailed)	.297
Exact Sig. (2-tailed)	0.301
Exact Sig. (1-tailed)	.151
Point Probability	.002
a. Grouping Variable: V3	

Comparison of Regression Analysis of Actual Cost Change of CII BM&M and RT-318 Survey datasets

In this section, we compare the regression model from each database to make sure there is no significant statistical difference between them. The Analysis of Cost Change Regression Models from CII BM&M and RT-318 Survey Projects are shown in Tables 17 and 18 and then both models are illustrated in Figure 24.

CII BM&M Projects Linear Regression Model:

Cost Overrun (%) = -7.70 + 8.69 × Staffing Difficulties

Table 17. CII BM&M Projects Cost Change Linear Regression Model

Summary of Fit

R Square	0.198776
R Square Adj	0.185641
Root Mean Square Error	15.4861
Mean of Response	-3.50794
Observations (or Sum Wgts)	63

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3629.302	3629.30	15.1335
Error	61	14628.984	239.82	**Prob > F**
C. Total	62	18258.286		0.0003*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-7.701607	2.229075	-3.46	0.0010*
Staffing Difficulties	8.6908298	2.234045	3.89	0.0003*

RT-318 Survey Projects Linear Regression Model:

Cost Overrun (%) = 0.83 + 8.33 × Staffing Difficulties

Table 18. RT-318 Survey Projects Cost Change Linear Regression Model

Summary of Fit

R Square	0.114882
R Square Adj	0.062816
Root Mean Square Error	20.99682
Mean of Response	8.442105
Observations (or Sum Wgts)	19

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	972.7610	972.761	2.2065
Error	17	7494.7313	440.867	**Prob > F**
C. Total	18	8467.4923		0.1557

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8289283	7.033623	0.12	0.9076
Staffing Difficulties	8.3275972	5.606221	1.49	0.1557
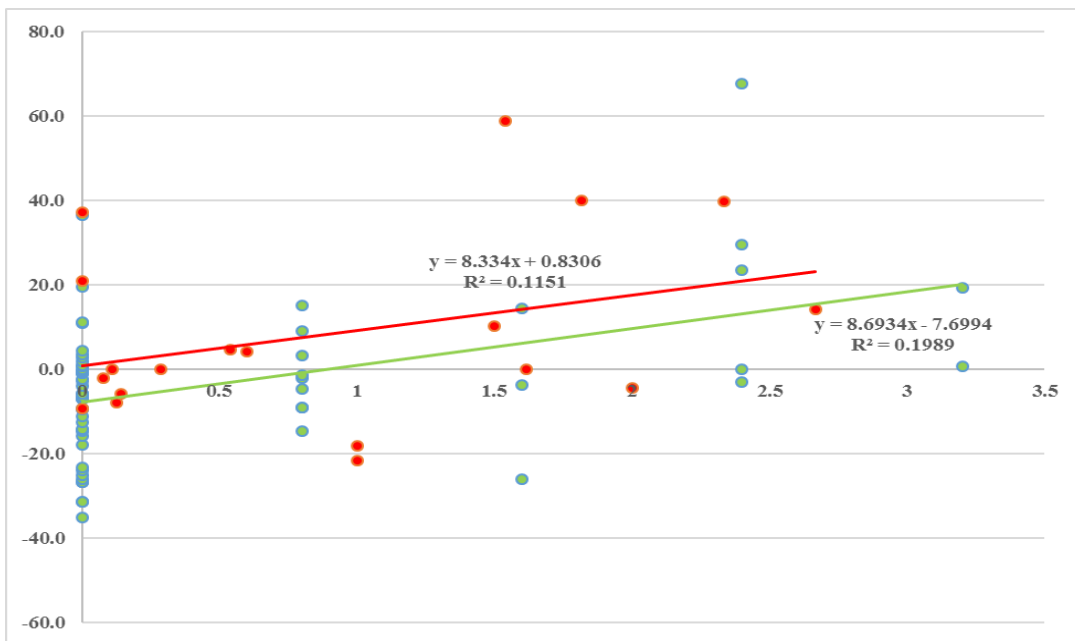
Figure 24. Cost Overrun Regression models of RT-318 and CII BM&M

The slopes in both models are almost similar, 8.69 comparing to 8.33, but the intercepts in equations are different. The intercepts in model from RT-318 Survey Data is 0.83 comparing to other of -7.7. The P-value of this parameter in RT-318 Data Model is 0.9076

which means it is far from to be statistically significant. The P-value for this parameter in model from CII BM&M data is 0.001 which means it is statistically significant at 0.001 level. In the section 4.7.2 we will show that the intercept of main model comes from whole dataset is close to BM&M model's one. However, to make sure the slope of two models have no statistically significant difference, we construct the 95% Confidence Interval for slope Coefficients. If these Confidence Intervals have overlap, it means they are not statistically significant different from each other (α=0.05). The Confidence Interval for slope can be calculated as: (Agresti and Finlay, 2009)

$$b \pm t \,(se)$$

in which t-score is the value from t Distribution with df = n–2 for desired confidence level. The Table 19 shows the 95% CI for each slope coefficient of models.

Table 19. 95% CI for slopes of Cost Overrun Regression models of RT-318 and CII BM&M

Model	slope Coefficient	se	df = n-2	$t_{.025}$	Lower 95% CI	Upper 95% CI
RT-318	8.32	5.61	17	2.11	-3.52	20.16
CII BM&M	8.69	2.23	61	2	4.23	13.15

As shown in the Table 19, the 95% CI of both models have overlap. Therefore, we can state that the slope coefficients of models have no statistically significant difference.

Comparison of Regression Analysis of Actual Time Change of CII BM&M and RT-318 Survey datasets

The Time Change Linear Regression Models constructed from CII BM&M and RT-318 Survey datasets are shown in Table 4.20 and 4.21 and then both illustrated in Figure 25.

CII BM&M Projects Linear Regression Model:

Y = 7.19 + 2.78 × Staffing Difficulties

Table 20. CII BM&M Projects Time Change Linear Regression Model

Summary of Fit

R Square	0.019915
R Square Adj	0.001765
Root Mean Square Error	17.21175
Mean of Response	8.419286
Observations (or Sum Wgts)	56

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	325.055	325.055	1.0973
Error	54	15997.192	296.244	**Prob > F**
C. Total	55	16322.247		0.2995

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	7.1892731	2.582424	2.78	0.0074*
X	2.7774478	2.651505	1.05	0.2995

RT-318 Survey Projects Linear Regression Model:

Y = -0.48 + 16.30× Staffing Difficulty

Table 21. RT-318 Survey Projects Time Change Linear Regression Model

Summary of Fit

R Square	0.256497
R Square Adj	0.210028
Root Mean Square Error	25.15807
Mean of Response	15.16
Observations (or Sum Wgts)	18

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3493.600	3493.60	5.5197
Error	16	10126.856	632.93	**Prob > F**
C. Total	17	13620.456		0.0320

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.480054	8.915067	-0.05	0.9577
X	16.301156	6.938397	2.35	0.0320
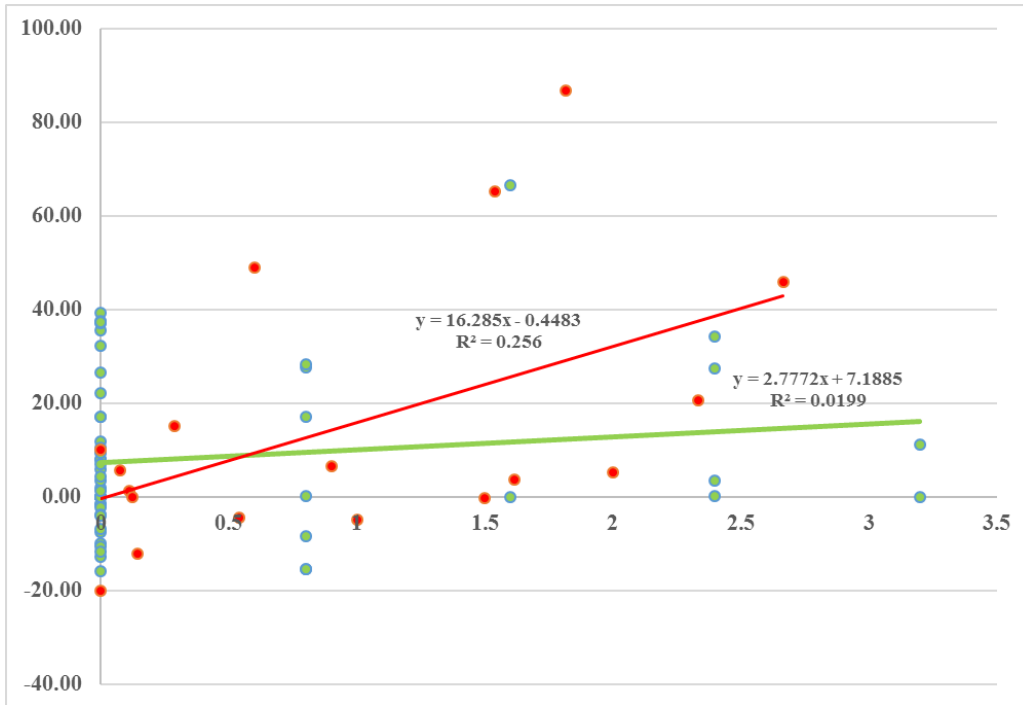
Figure 25. Time Overrun Regression models of RT-318 and CII BM&M.

Both models demonstrate an aligned relationship between increased staffing difficulties and increased Time Overrun. However, the slope in RT-318 Survey model is bigger than CII BM&M one, 16.3 comparing to 2.78. Since these parameters are very different, we need to examine whether this difference is statistically significant or not. Therefore, we construct the 95% Confidence Interval for the slope of both models. Table 4.22 shows the detail of analysis.

Table 22. 95% CI for slopes of Time Overrun Regression models of RT-318 and CII BM&M

Model	slope Coefficient	se	df = n-2	t.025	Lower 95% CI	Upper 95% CI
RT-318	16.3	6.94	16	2.12	1.5872	31.0128
CII BM&M	2.78	2.65	54	2	-2.52	8.08

As shown in the Table 22, the 95% CI of slope Coefficients of models have overlap therefore it can be stated that these two parameters have no statistically significant difference. However, both models are not statistically significant at 0.05 level. The model of BM&M has a P-value of 0.299 and the model from RT-318 Survey although has a P-value of 0.03, the intercept p-value is 0.95 which is very far to be statistically significant at 0.05 level.

Comparison of Regression Analysis of Safety Performance (TRIR) of CII BM&M and RT-318 Survey datasets

The Poisson regression analysis of BM&M and RT-318 Survey Data on TRIR are shown in Tables 23 and 24.

CII BM&M Projects Poisson Regression Model

$Y = e^{\,0.56X-1.40}$

Table 23. CII BM&M Projects TRIR Poisson Regression Model

Model Information		
Data Set	WORK.A	
Distribution	Poisson	
Link Function	Log	
Dependent Variable	Y1	Y1

Number of Observations Read	37
Number of Observations Used	37

Criteria For Assessing Goodness Of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	35	29.9720	0.8563
Scaled Deviance	35	29.9720	0.8563
Pearson Chi-Square	35	35.4406	1.0126

Scaled Pearson X2	35	35.4406	1.0126
Log Likelihood		-25.2498	
Full Log Likelihood		-28.0968	
AIC (smaller is better)		60.1936	
AICC (smaller is better)		60.5465	
BIC (smaller is better)		63.4154	
Algorithm converged.			

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept	1	-1.4019	0.3691	-2.1253	-0.6785	14.43	0.0001
X1	1	0.5567	0.1963	0.1720	0.9413	8.05	0.0046
Scale	0	1.0000	0.0000	1.0000	1.0000		

RT-318 Survey Projects Poisson Regression Model

$Y = e^{0.3X-1.1}$

Table 24. RT-318 Survey Projects TRIR Poisson Regression Model

Model Information		
Data Set	WORK.A	
Distribution	Poisson	
Link Function	Log	
Dependent Variable	Y2	Y2

Number of Observations Read	37
Number of Observations Used	13
Missing Values	24

Criteria For Assessing Goodness Of Fit			
Criterion	DF	Value	Value/DF
Deviance	11	10.1349	0.9214
Scaled Deviance	11	10.1349	0.9214
Pearson Chi-Square	11	9.4854	0.8623
Scaled Pearson X2	11	9.4854	0.8623
Log Likelihood		-10.2973	
Full Log Likelihood		-10.7108	
AIC (smaller is better)		25.4215	
AICC (smaller is better)		26.6215	
BIC (smaller is better)		26.5514	

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-1.1011	0.6794	-2.4328	0.2306	2.63	0.1051
X2	1	0.2950	0.4943	-0.6737	1.2638	0.36	0.5506
Scale	0	1.0000	0.0000	1.0000	1.0000		

Both models demonstrate an aligned relationship between increased staffing difficulties and increased TRIR. The parameters of model from the RT-318 Survey Data is slightly different from BM&M model, X: 0.3 comparing to 0.52 and Interpret -1.1 comparing to -1.4, but as shown the last Table for each analysis, the Wald 95% Confidence Limits for each parameter in both models have overlap. Therefore, we can state that there is no statistical significant difference between two models. In overall, both models demonstrate almost similar relationship between Staffing Difficulty and TRIR in construction projects.

Discussion and Conclusion

we compared five variables from two datasets of CII BM&M and RT-318 Survey Projects to make sure there is no significant difference between them and therefore combining two

databases is appropriate. We conducted Mann-Whitney test to examine whether there is significant difference between distribution of Actual Cost, Actual Cost Change, Actual Time Change, and Safety Performance (TRIR). We could not perform Mann-Whitney test to analyze the two datasets in relation to project duration because the distribution of this parameter is not similar. The result of test demonstrates that there is no significant difference ($\alpha=0.05$) between two datasets in these parameters. Since we want to conduct the regression analysis on Cost Change, Time Change and TRIR, we also perform regression analysis on these parameters in each dataset. The result again shows no significant difference between regression models constructed from each dataset.

In Conclusion, we can state that constructing new database with combining CII BM&M and RT-318 Survey Projects is appropriate and result in bigger and more reliable database for assessing the impact of craft labor shortage on construction project performance.

4. Craft Labor Availability Impact on Project Performance

Comparison of Average Actual Cost Change and Actual Time Change between Projects with & without workforce shortage (RT-318 Survey Projects)

In the Survey RT-318 Question No.16, respondents are asked whether their project performances were impacted by workforce shortage or not. Therefore, projects in this set of data can be categorized into two groups, project impacted by workforce shortage and project not impacted by workforce shortage. Since the data of the CII BM&M does not have the question specifically asks about the impact of craft labor shortage, this set of the data is excluded in this analysis. The Table 25 shows the overview of total data of RT-318 Survey categorized into two groups with regards to the workforce shortage impact.

Table 25. Overview of Total Data of RT-138 Survey

Overview of Total Data	Projects **Not Impacted** by workforce shortage	Projects **Impacted** by workforce shortage
No. of Projects	14	14
Average Actual Cost ($M) (Median, Min, Max)	**156.56** (33.5, 3.6, 1120)	**769.52** (45, 6, 8549)
Average Actual duration (Day) (Median, Min, Max)	**503.62** (577, 151, 1085)	**614** (533, 134, 1684)
Average OSHA Total Number of Recordable Incident Cases per 200,000 Actual direct work hour (Median, Min, Max)	**0.94** (0.37, 0, 2.86)	**3.53** (0.84,0, 17.06)
No. of Outliers	3	2

As it is shown in the Table 25, the data has five outliers which are excluded from our analysis. The Table 26 shows the detail and reasons why these projects are considered as outliers. Project No. 4 & 9 and 29 has more than 150% cost overrun and has 200%, 78% and 122% Schedule Over respectively. Project No.15 is ongoing project and has no stop date data. The responded of Project No.16 has specifically mentioned that there has been large amount of scope change in this project, therefore we decided to exclude it from our analysis.

Table No.26. Outliers of Data of Survey RT-138

Project No.	Cost Overrun	Time Overrun	Impacted by workforce shortage	Reason of exclusion
4	168%	200%	No	Extreme Cost and Time Overrun
9	208%	78%	Yes	Extreme Cost and Time Overrun
15	-33%	ongoing	No	The Ongoing Project (No Stop Date Data)
16	108%	64%	Yes	Large Amount of Scope Change
29	149%	122%	No	Extreme Cost and Time Overrun

To choose an appropriate statistical test for comparing the project performance in these two groups of project, first of all, we need to see the distribution of these variables in each group. The Figures 26 to 31 show the Distribution, Total Number and Mean of these data points.
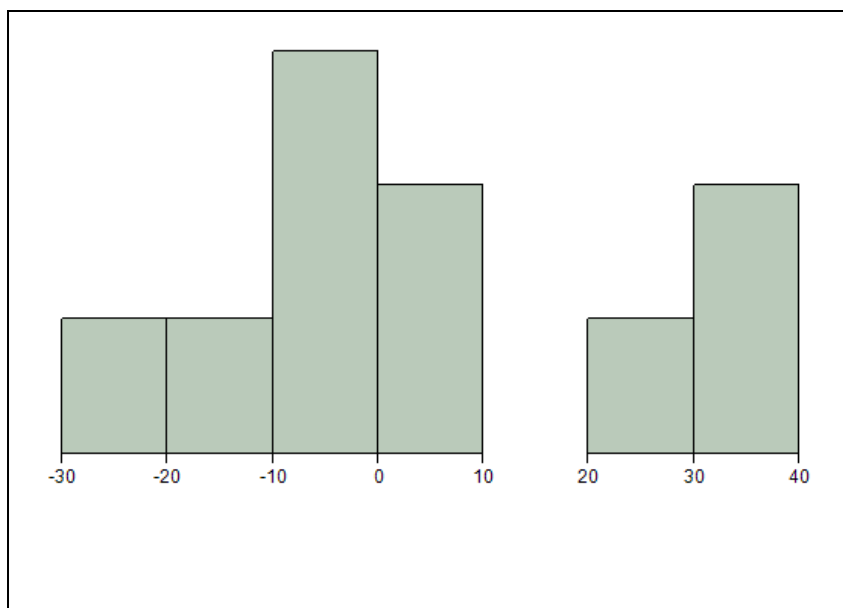
Figure 26. Distribution of Cost Change of projects Not Impacted by a workforce shortage (RT-318 Survey Data) (Mean=4.14)
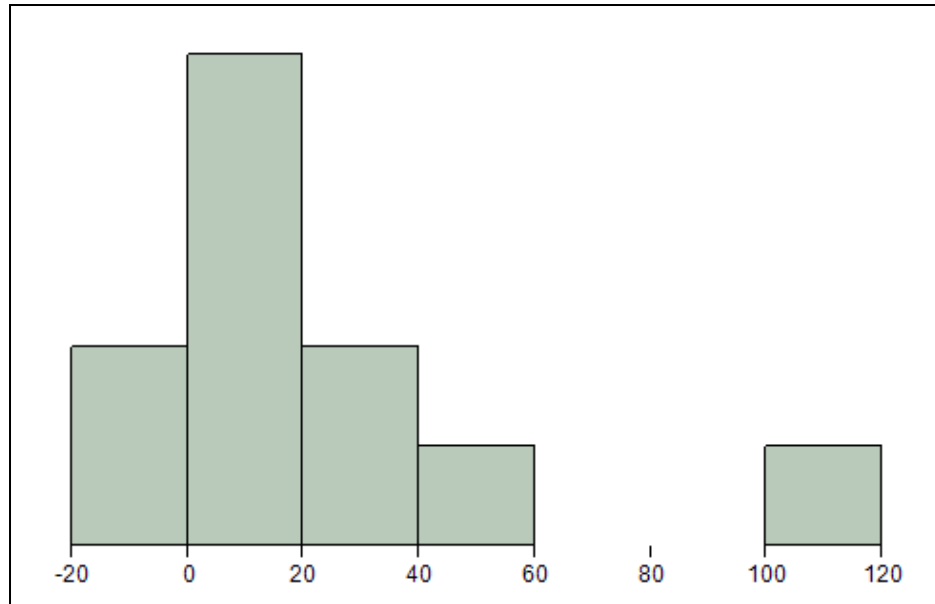
Figure 27. Distribution of Cost Change of 11 projects Impacted by a workforce shortage (RT-318 Survey Data) (Mean= 23.65)
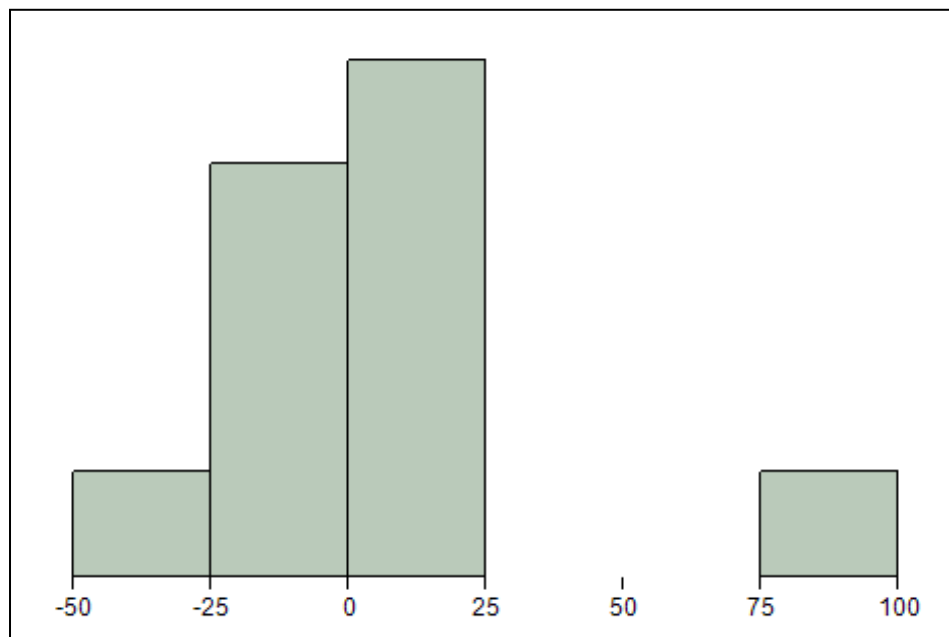
Figure 28. Distribution of Time Change of 11 projects Not Impacted by a workforce shortage (RT-318 Survey Data) (Mean= 4.49)
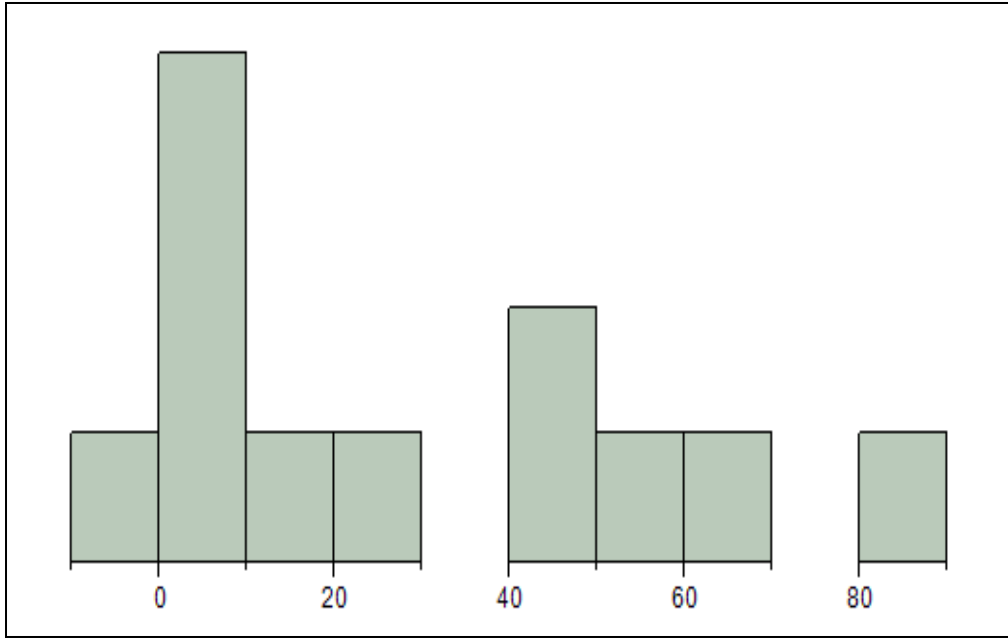
Figure 29. Distribution of Time Change of 12 projects Impacted by a workforce shortage (RT-318 Survey Data) (Mean= 29.17)
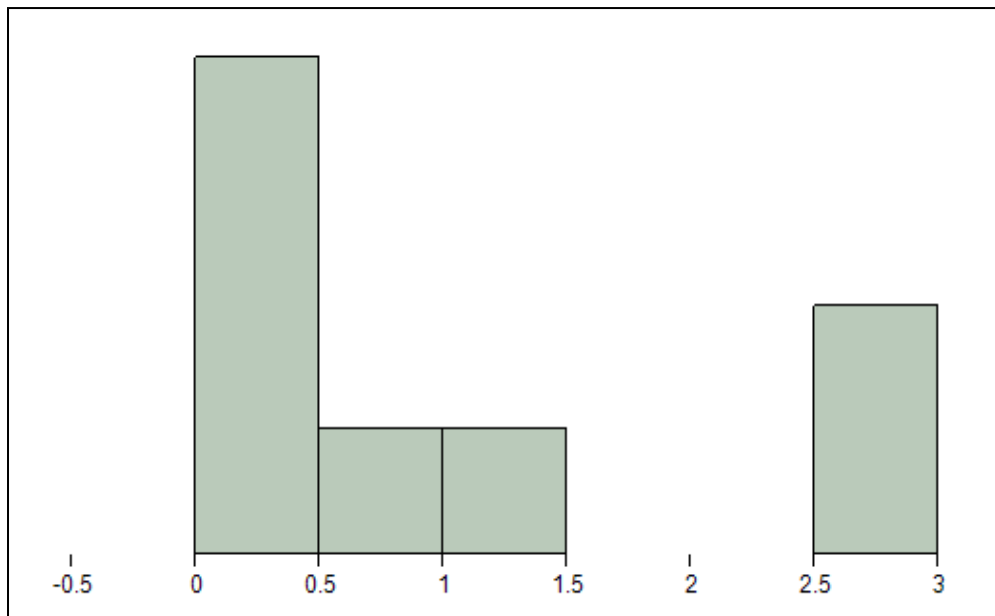
Figure 30. Distribution of Total Number of Recordable Incident Cases per 200,000 Actual direct work hour of 12 projects Not Impacted by a workforce shortage (RT-318 Survey Data) (Mean= 0.94)
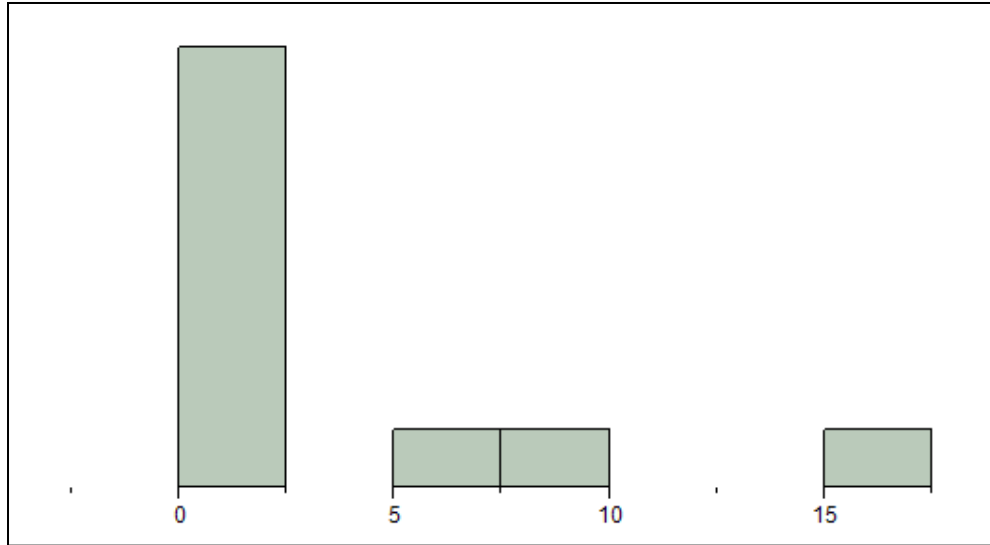
Figure 31. Distribution of Total Number of Recordable Incident Cases per 200,000 Actual direct work hour of 11 projects Impacted by a workforce shortage (RT-318 Survey Data) (Mean=3.53)

Since the distribution of Cost Change and Time Change variables have slightly departure from normality and comparing Mean with T-Test is robust to violation of normality, we conduct the T-Test to compare the mean in these two variables. The justification to use this test will be provided later in this section. We also perform Mann-Whitney Test to compare the distribution of these variables in two groups in the next section.

Agresti and Finlay (2009) argue that T-Test does not work so well for a one-sided test with small n when the population distribution is highly skewed. Therefore, because the data points of Safety Performance (TRIR) are highly skewed in both two groups, we cannot perform T-Test to compare the Means of this parameter. However, since they both have similar distributions, we can perform Mann-Whitney Test to compare the distribution of these variables in two groups which will be provided later.

Assumptions of Significance T-Test: (Agresti and Finlay, 2009)

1. Quantitative Variable: all variables are Quantitative Continues variable

2. Randomization: All data are obtained randomly.

3. Normal population distribution: The data points of Time and Cost Change has slight departure from normality in both groups of impacted and not impacted projects. In practice, this comparing of two means method is robust to a violation of the normal population assumption as argued by Agresti and Finlay (2009). We need to be wary of extreme outliers or extreme skew that may make the mean unsuitable as a summary measure (Agresti and Finlay, 2009). In all groups of projects in Table 25, with the exception of Safety performance data, there is no extreme outlier.

4. Independent variable: all variables are independent from each other.

    Ho: Mean (Impacted project) = Mean (Not Impacted project)

    Ha: Mean (Impacted project) > Mean (Not Impacted project)

    We use one tail probability for P-value, Significance level (α) = 0.05

Table 27 shows the detail and result of our analysis. As shown in this Table, the average Cost Overrun and Time Overrun in projects impacted by craft labor shortage is much higher, about 550% more, than those not impacted by workforce shortage. The P-value in both tests shows that this difference is statistically significant at 0.05 level.

Table 27. Comparison of Project Performances between Projects with & without impact of workforce shortage (RT-318 Survey Data)

Project Performance Parameters	Project Not Impacted by workforce shortage			Projects Impacted by workforce shortage			T (one tail)	Df	P
	Mean	SD	N	Mean	SD	N			
Change of Actual Construction Cost to Budgeted one (%)	**4.14**	19.68	10	**23.65**	33.04	11	1.66	19	**0.051**
Change of Actual Construction Time to Planned one (%)	**4.49**	31.28	11	**29.17**	28.25	12	1.98	21	**0.031**

Comparing Distribution of Actual Cost Change, Time Change, and TRIR between project Impacted and Not Impacted by Workforce Shortage using Mann-Whitney Test (RT-318 Survey Projects):

The Mann-Whitney Statistics

Ho: F (t) = G (t)   for every t   or

Ho: The distribution of scores for two groups are equal

F: distribution of sample 1 (X), G: distribution of sample 2 (Y)

The alternative hypothesis is that the Y tends to be larger than X.

Ha: G (t) = F (t-Δ)   for every t   or

Ha: The distribution of scores for sample 2 (Y) is higher than that in sample 1(X)   or

Ha: The mean rank in sample 2 (Y) is higher than that is sample 1 (X)

Assumption of the Mann-Whitney Test (Hollander et. all, 2014):

- The observations in both samples are random and independent from each other

- The variable is Quantitative Continuous variable

Both assumptions are satisfied for these data sets. The Significance level (α) is 0.1. Table 4.28-30 shows the result of Mann-Whitney Test for comparing whole distribution of Actual Cost Change, Actual Time Change and TRIR in RT-318 Projects of impacted and not impacted by workforce shortage.

Table 28. Mann-Whitney Test, Comparison of Distribution of Actual Cost Change

Ranks				
	VAR00001	N	Mean Rank	Sum of Ranks
Cost Increase	.00	10	8.80	88.00
	1.00	11	13.00	143.00
	Total	21		

Test Statistics	
	Cost Increase
Mann-Whitney U	33.000
Wilcoxon W	88.000
Z	-1.550
Asymp. Sig. (2-tailed)	.121
Exact Sig. [2*(1-tailed Sig.)]	.132[b]
Exact Sig. (2-tailed)	.127
Exact Sig. (1-tailed)	**0.064**
Point Probability	.004

Table 29. Mann-Whitney Test, Comparison of Distribution of Actual Time Change

Ranks				
	VAR0001	N	Mean Rank	Sum of Ranks
Time Increase	.00	11	8.77	96.50
	1.00	12	14.96	179.50
	Total	23		

Test Statistics	
Mann-Whitney U	30.500
Wilcoxon W	96.500
Z	-2.185
Asymp. Sig. (2-tailed)	.029
Exact Sig. [2*(1-tailed Sig.)]	.027[b]
Exact Sig. (2-tailed)	.028
Exact Sig. (1-tailed)	**0.014**
Point Probability	.001

Table 30, Mann-Whitney Test, Comparison of Distribution of TRIR

Ranks				
	V3	N	Mean Rank	Sum of Ranks
TRIR	0	7	7.00	49.00
	1	10	10.40	104.00
	Total	17		

Test Statistics	
Mann-Whitney U	21.000
Wilcoxon W	49.000
Z	-1.397
Asymp. Sig. (2-tailed)	.163
Exact Sig. [2*(1-tailed Sig.)]	.193[b]
Exact Sig. (2-tailed)	.175
Exact Sig. (1-tailed)	**0.088**
Point Probability	.009
a. Grouping Variable: V3	

The P-value of the Mann-Whitney Test for the difference in whole distribution in Cost Change, Time Change and TRIR is 0.064, 0.014 and 0.088 respectively. The result demonstrates that the distribution of these variables tends to be higher when a project is impacted by craft labor shortage. This difference is statistically significant at the 0.1 level.

Comparing Means of Actual Cost Change, Time Change, and TRIR between projects with and without Staffing Difficulty (Research Database: CII BM&M and RT-318 Survey Data):

We also can compare the performance of projects with regard to their experience of staffing difficulty. The data used in this analysis consists of RT-318 Survey and CII BM&M Data. After conversion of the labor availability score from the CII BM&M into RT-318 Survey scale, discussed in section 4.4, we have a set of projects that had staffing difficulty (Score > 0) or projects that had no staffing difficulty (Score=0). We divided all projects into two groups based on these scores and conducted the T-Test to check whether there is significant difference between average projects performance in these two groups. In the following,

firstly, we discuss the assumptions of T-Significance Test and then result of test will be provided in Table 31.

Assumption of T-Test: (Agresti and Finlay, 2009)

1. Quantitative Variable: all variables are Quantitative Continues variable

2. Randomization: All data are obtained randomly

3. Normal population distribution: Agresti and Finlay (2009) mentioned that this method of comparing is robust to the violation of the normal population assumption especially when both n_1 and n_2 are at least 30. All groups of data points in Cost Change and Time Change in this analysis have more than 30 data points which means this analysis is reliable even if there are departures from normality in data sets. In the following, we provide the distribution of all 6 groups. All groups have similar normal or slight departure from normality except the data sets for safety performance which are right skewed.
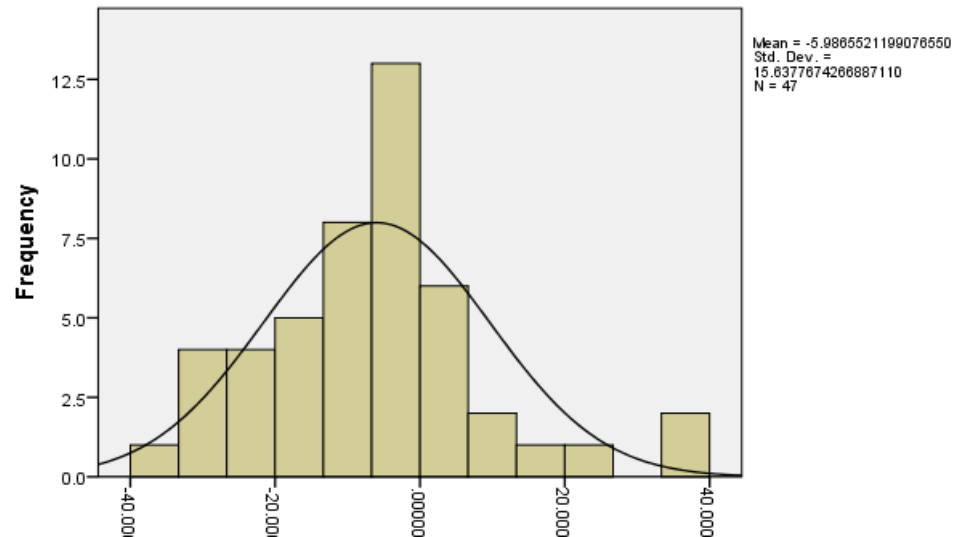
Figure 32. Distribution of Cost Change of projects without staffing difficulty
(CII BM&M & RT-318 Survey Data)
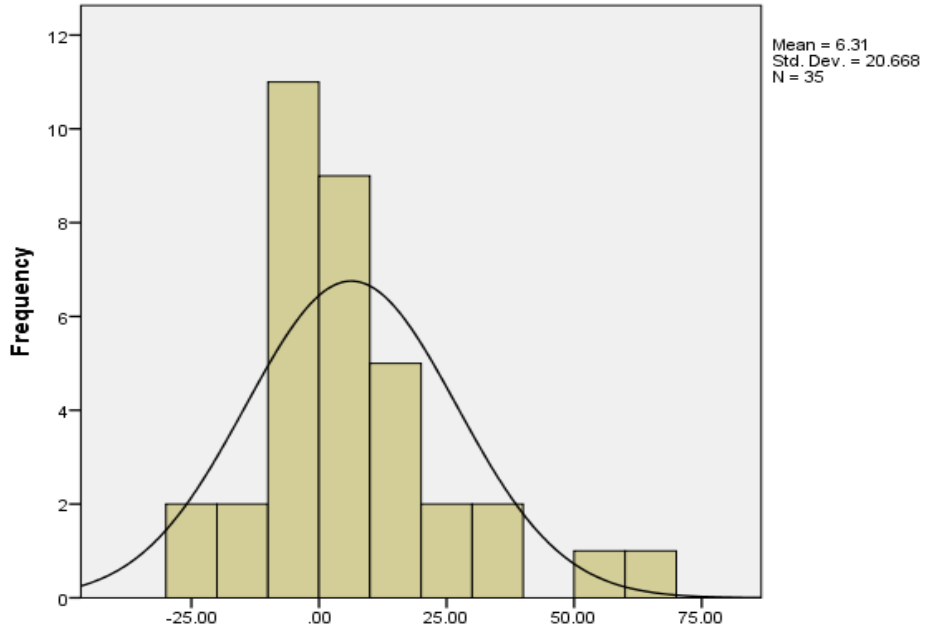
Figure 33. Distribution of Cost Change of project with staffing difficulty (CII BM&M & RT-318 Survey Data)
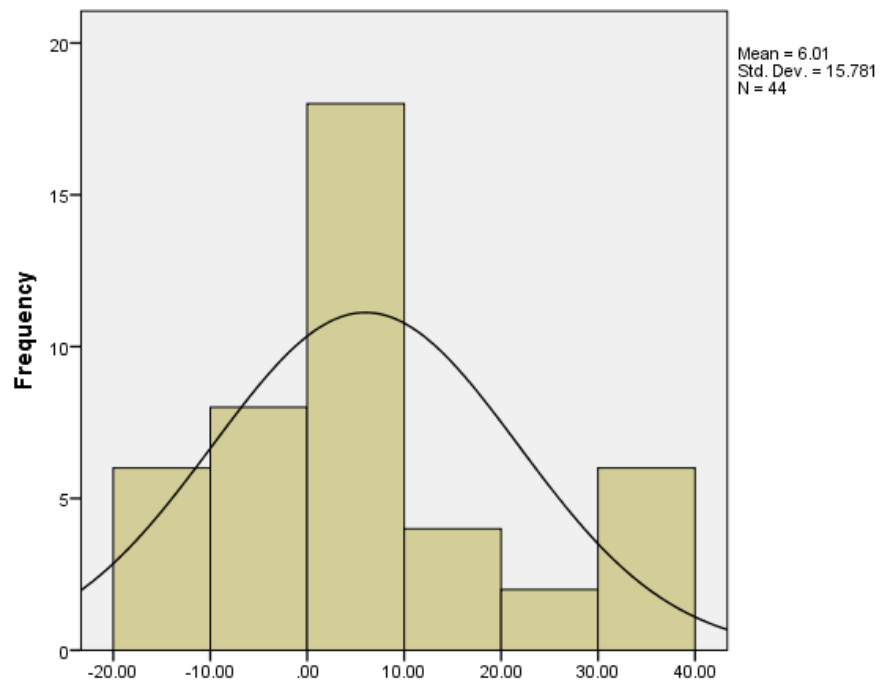
Figure 34. Distribution of Time Change of projects without staffing difficulty (CII BM&M & RT-318 Survey Data)
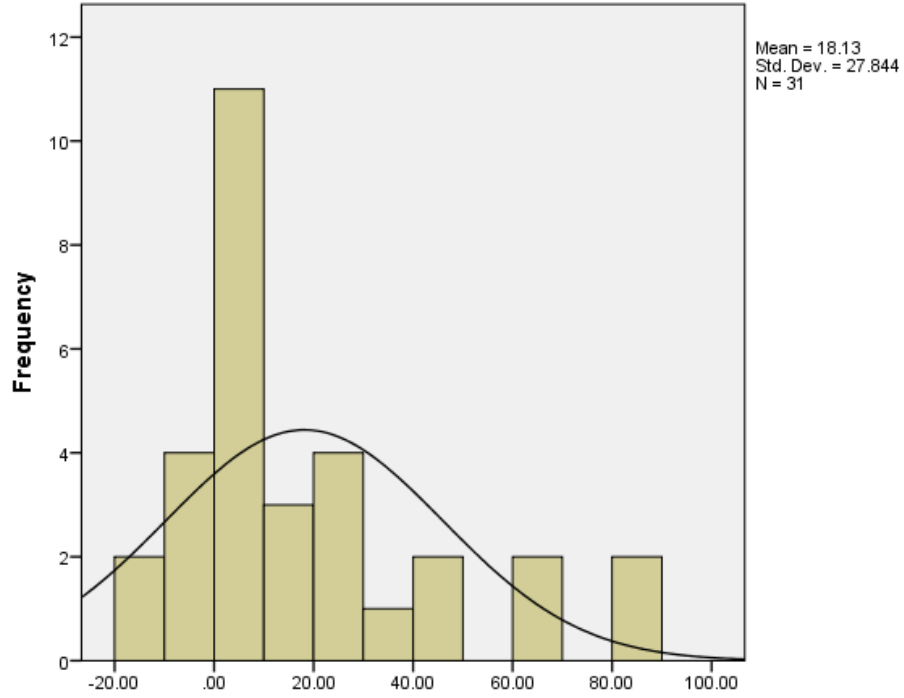
**Figure 35. Distribution of Time Change of project with staffing difficulty
(CII BM&M & RT-318 Survey Data)**
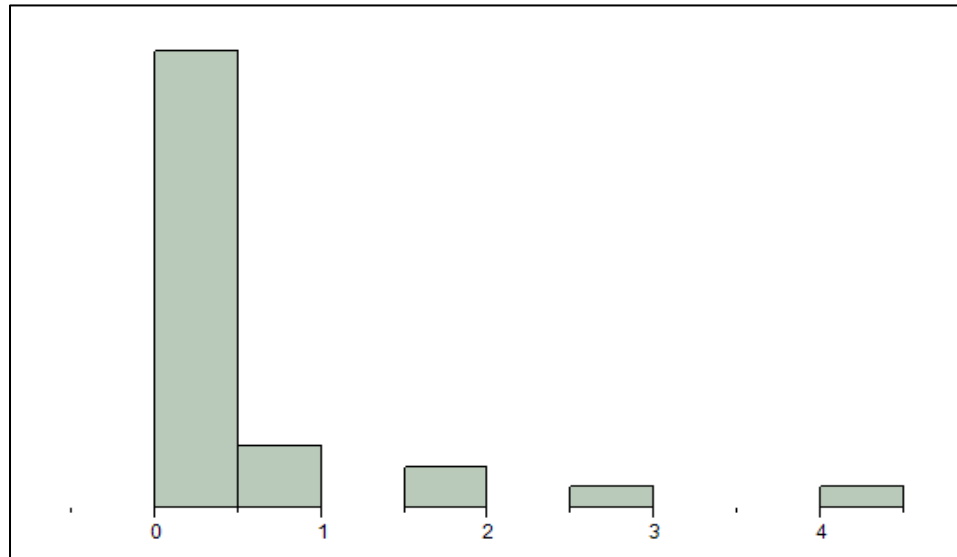
**Figure 36. Distribution of Total Number of Recordable Incident Cases per 200,000 Actual direct
work hour of projects without staffing difficulty (CII BM&M & RT-318 Survey Data)**
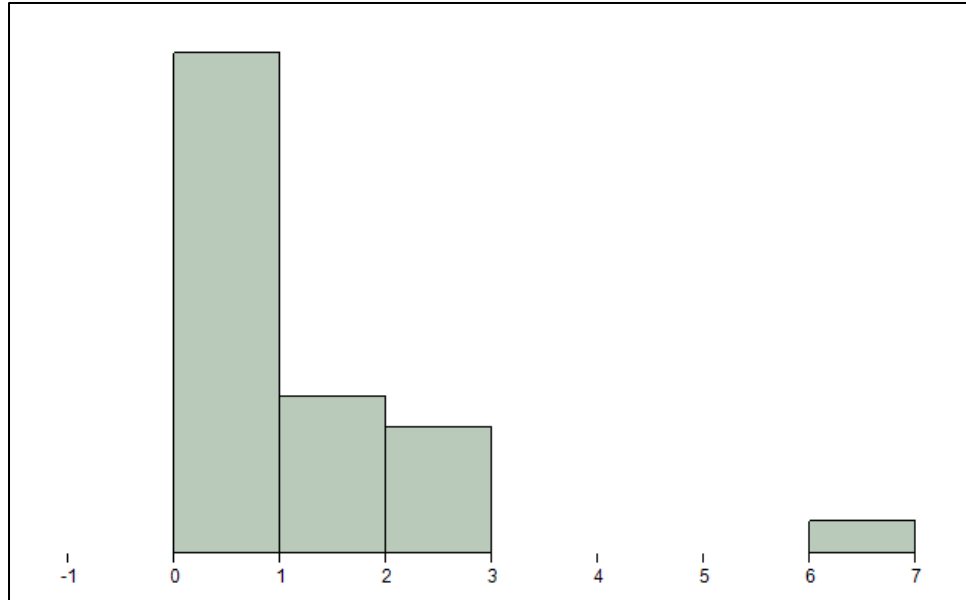
Figure 37. Distribution of Total Number of Recordable Incident Cases per 200,000 Actual direct work hour of projects with staffing difficulty (CII BM&M & RT-318 Survey Data)

4. Independent variable: all variables are independent from each other.

Ho: Mean (Impacted project) = Mean (Not Impacted project)

Ha: Mean (Impacted project) > Mean (Not Impacted project)

Significance level (α) = 0.05

The detail and result of test is provided in Table 31.

Table 31. Comparison of Project's Cost and Time Performances between Projects with & without Staffing Difficulty (RT-318 Survey and CII BM&M Data)

Project Performance Parameters	Staffing Difficulties = 0			Staffing Difficulties > 0			T (one tail)	Df	P-Value
	Mean	SD	N	Mean	SD	N			
Change of Actual Construction Cost to Budgeted one (%)	-6.0[1]	15.47	47	**6.3**	20.37	35	2.99	80	**0.0018**
Change of Actual Construction Time to Planned one (%)	**6.01**	15.60	44	**14.83**	24.97	31	1.74	73	**0.0429**
OSHA Total Number of Recordable Incident Cases per 200,000 Actual Direct Work Hour (TRIR)	**0.30**	0.64	27	**0.68**	0.776	23	1.85	48	**0.035**

1. There are projects with actual cost < estimated cost

As shown in Table 31, there is significant difference between Cost Overrun, Time overrun and TRIR in projects that experienced staffing difficulty comparing to those had no staffing difficulty. These difference is statistically significant at 0.05 level for all three parameters.

Comparing Distribution of Actual Cost Change, Time Change, and TRIR between projects with and without Staffing Difficulty using Mann-Whitney Test (Research Database: CII BM&M and RT-318 Survey Data):

In previous section, since the Cost Change and Time change data points have slight departure from normality, and also TRIR data point are right skewed, we also perform the Mann-Whitney test to demonstrate the impact of staffing difficulty on construction project performance.

The Mann-Whitney Statistics

Ho: F (t) = G (t)   for every t   or

Ho: The distribution of scores for two groups are equal

F: distribution of sample 1 (X), G: distribution of sample 2 (Y)

The alternative hypothesis is that the Y tends to be larger than X.

Ha: G (t) = F (t-Δ)   for every t   or

Ha: The distribution of scores for sample 2 (Y) is higher than that in sample 1(X)   or

Assumption of the Mann-Whitney Test (Hollander et. all, 2014):

- The observations in both samples are random and independent from each other.

- The variable is Quantitative Continues variable.

Both assumptions are satisfied for these data sets. The Significance level (α) is 0.05.

Considering distribution of variables provided in figures 32-37, each variable has almost

similar distribution of data points for projects with and without staffing difficulty.

Therefore, we can compare each pair of distribution of variables using Mann-Whitney Test.

The Tables 32-34 shows the result of this test for these three project performances.

Table 4.32. Mann-Whitney Test for Cost Change comparison

Ranks				
	VAR01	N	Mean Rank	Sum of Ranks
Cost overrun (%)	SD=0	47	34.98	1644.00
	SD>0	35	50.26	1759.00
	Total	82		

Test Statistics	
Mann-Whitney U	516.000
Wilcoxon W	1644.000
Z	-2.874
Asymp. Sig. (2-tailed)	.004
Exact Sig. (2-tailed)	.004
Exact Sig. (1-tailed)	**0.002**
Point Probability	.000
a. Grouping Variable: VAR00001	

Table 33, Mann-Whitney Test for Time Change comparison

Ranks				
	Staffing Difficulties	N	Mean Rank	Sum of Ranks
	.0	44	34.40	1513.50
Time overrun (%)	1.0	31	43.11	1336.50
	Total	75		

Test Statistics	
Mann-Whitney U	523.500
Wilcoxon W	1513.500
Z	-1.707
Asymp. Sig. (2-tailed)	.088
Exact Sig. (2-tailed)	.088
Exact Sig. (1-tailed)	**0.044**
Point Probability	.001
a. Grouping Variable: Staffing Difficulties	

Table 34, Mann-Whitney Test for Safety Performance (TRIR) comparison

	Ranks			
	X	N	Mean Rank	Sum of Ranks
Y	SD=0	27	21.07	569.00
	SD>0	23	30.70	706.00
	Total	50		

Test Statistics	
Mann-Whitney U	191.000
Wilcoxon W	569.000
Z	-2.665
Asymp. Sig. (2-tailed)	.008
Exact Sig. (2-tailed)	.007
Exact Sig. (1-tailed)	**0.004**
Point Probability	.000
a. Grouping Variable: X	

The P-value of the test for Cost Change, Time Change and TRIR is 0.002, 0.044 and 0.004 respectively which indicates that the result is significant at 0.01 level for Cost Change and TRIR and 0.05 level for Time Change. Overall, the result of analysis demonstrates that the distribution of the Cost Change, Time Change and TRIR data points in projects with staffing difficulty tend to be higher than that of projects had no staffing difficulty.

Discussion and Conclusion

The comparison analysis of construction projects performance with regard to the craft labor shortage issue shows that there is significant difference between project performance that experienced skilled craft shortage

/h and performance of projects did not have craft labor shortage.

The average Cost Overrun in projects impacted and projects not impacted by labor shortage in RT-318 Survey projects is 23.65% and 4.14% respectively. The Average Schedule Overrun is 4.49% when there is no impact of labor shortage and is 29.17% for projects experienced labor shortage. These differences are statistically significant at 0.05 level.

Comparison of projects performance in our research database (RT-318 Survey & CII BM&M) regarding two situations that there has been, at least, some measure of staffing difficulty in project or there has been no staffing difficulty shows consistent result. The Average Cost Change in projects experienced no staffing difficulty is -6.0% comparing to 6.3% when projects experienced staffing difficulty. This difference is statistically significant at 0.01 level. The Average Schedule Change in projects with no staffing difficulty is 6.01% comparing to 14.83% when projects experienced staffing difficulty. This difference is statistically significant at 0.05 level. The Average TRIR in group of projects with no staffing difficulty is 0.30 comparing to average of 0.68 for projects that had staffing difficulty. This difference also is statistically significant at 0.05 level.

In addition to the comparison analysis of the Mean, Using Mann-Whitney Test, we also compared the whole distribution of these performance parameters in RT-318 Survey Projects only and also in whole database of the study. The distributions of Cost Overrun, Schedule Overrun and TRIR in RT-318 Survey projects are higher for groups of projects that experienced craft labor shortage comparing those projects with no craft labor shortage. The P-values of tests are 0.064, 0.014 and 0.088 respectively which indicate that difference in Cost Overrun and TRIR distribution is significant at 0.1 level and the difference for Schedule Overrun is significant at 0.1 level.

The result of Mann-Whitney Test in comparing distributions of two groups of projects in research database again shows the consistent result. The P-values of tests for difference of Cost Overrun, Schedule Overrun and TRIR distribution are 0.002, 0.044 and 0.004 respectively. The result again demonstrates the higher distributions of these performance parameters when there is staffing difficulty.

6. Quantitative Risk Analysis of Craft Labor Shortage impact on Cost, Schedule, and Safety performance of Construction Projects

Table 35. Variable of Regression Analysis

Variable	Type	Regression Model
Actual Cost Change (%)	Quantitative, Continuous Variable	Simple Linear
Actual Schedule Change (%)	Quantitative, Continuous Variable	Simple Linear
TRIR	Quantitative, Continuous Variable	Poisson
Staffing Difficulty	Categorical (Qualitative), Ordinal Variable which is treated as a Quantitative, Interval, Continuous Variable	-

The decision about linear regression models was made by plotting the data and trying several different plausible models. Finally, we found that the linear model is the best fit model for these two variables. The significance level of 0.05 was selected to check the statistically significance of our regression models and variables. The software SAS9.4 is

used for this analysis. The staffing difficulty scale is the scale that used in RT-318 Survey which are shown in Table 36.

To check the appropriateness of assigned scores to staffing difficulty levels, we need to conduct the Sensitivity Analysis to make sure the conclusion of the analysis would not differ significantly if we chose other different scores (Finlay and Agresti 2009). This analysis will be conducted after regression analysis and will be discussed later,

Table 36. Levels of impact of staffing difficulties and assigned scores

Level	Definition	Score
No difficulty	There was no shortage. Able to staff the project with no delay on construction	0
Slight	Staffing difficulties led to consumption of schedule float and/or contingency	1
Moderate	Staffing difficulties led to delay of completing project activities on time	2
Severe	Staffing difficulties led to delay of completing project milestones	3
Very Severe	Staffing difficulties led to project delay	4

Linear Regression Analysis of the Relationship between Cost Overrun and Staffing Difficulty

Total number of projects used in this analysis is 82. Table No.37 shows the detail of Analysis of Variance for whole model and Table No.4.38 shows its Parameter Estimates analysis.

Table No 37 Analysis of Variance for whole regression model of relationship between Staffing Difficulty and Cost Overrun in Construction projects

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	5738.60020	5738.60020	19.90	<.0001
Error	80	23068	288.35532		
Corrected Total	81	28807			

Table No 38 Analysis of Parameter Estimate of the regression model of relationship between Staffing Difficulty and Cost Overrun in Construction projects

Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	-6.21722	2.24186	-2.77	0.0069
X	X	1	9.41162	2.10972	4.46	<.0001

The Model Equation is "Cost overrun (%) = -6.217+ 9.411 × Staffing Difficulties" and the R-square is 0.2. The model is statistically significant at 0.0001 level. Figures 38 shows the linear regression model with its 95% Confidence Interval which illustrates the relationship between Staffing Difficulty and Actual Cost Change in construction projects.
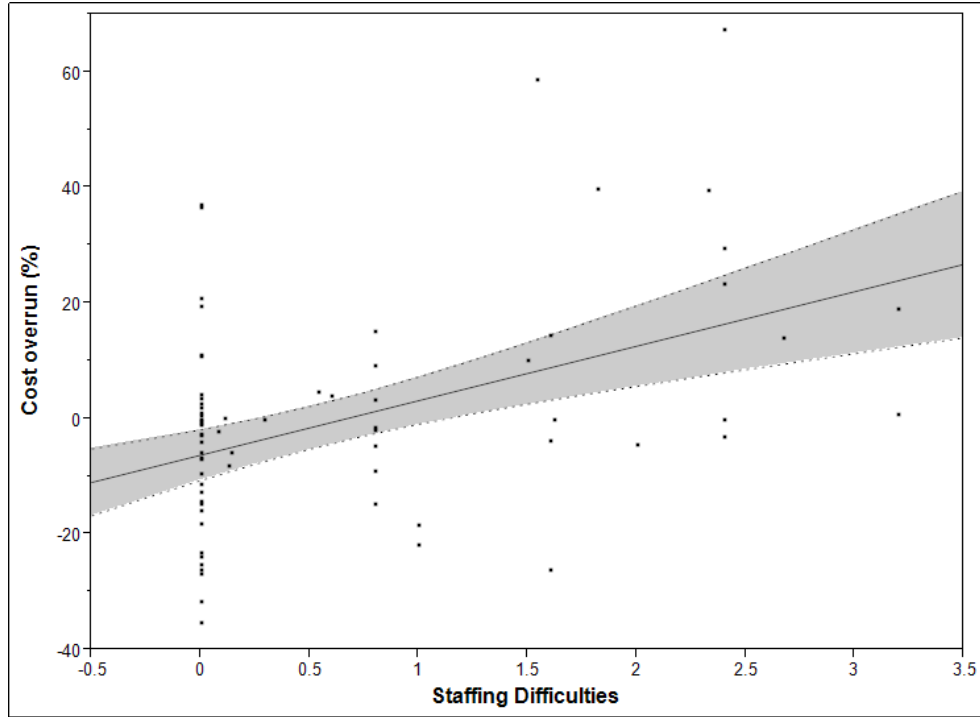
Fig 38. The regression model and its 95% CI of relationship between Staffing Difficulty and Cost Overrun in Construction projects (number of projects used: 82)

Diagnostic Tests

In order to examine the reliability of models, diagnostic tests should be performed on model. The residual plot of models, shown in Fig. 39, demonstrates that the residuals are randomly distributed in a band around the horizontal line of zero. The variance of error is also almost constant across the data in this Figure. Therefore, it can be stated that the assumption of the homogeneity of variance is not violated and errors are statistically independent in our model. Moreover, the points in the plots of Figure 4.40 lie nearly along a straight line which indicates the error are distributed normally in the Cost Overrun model.
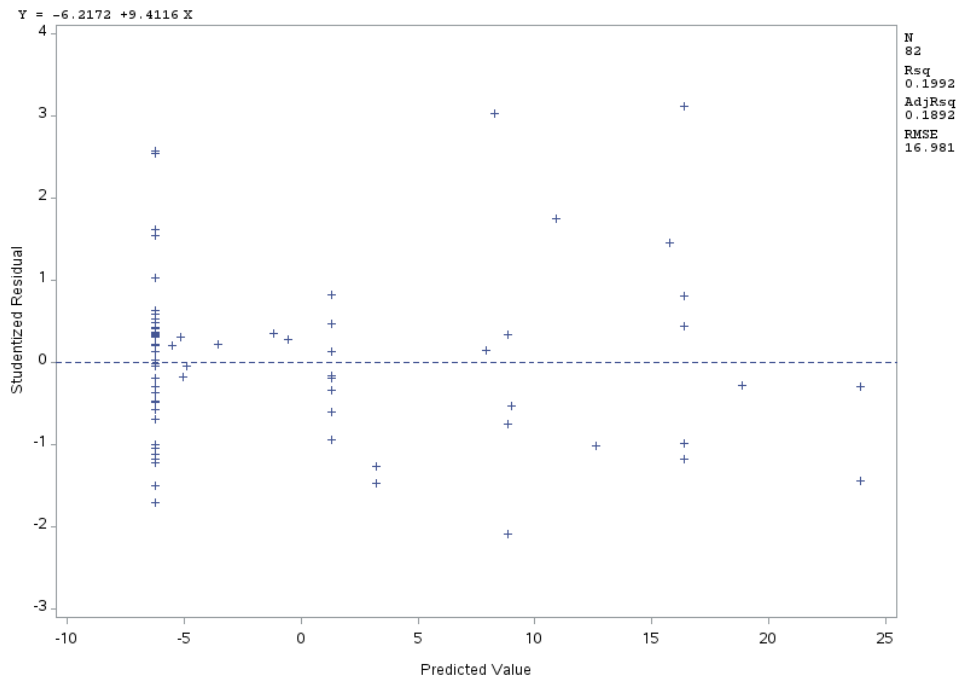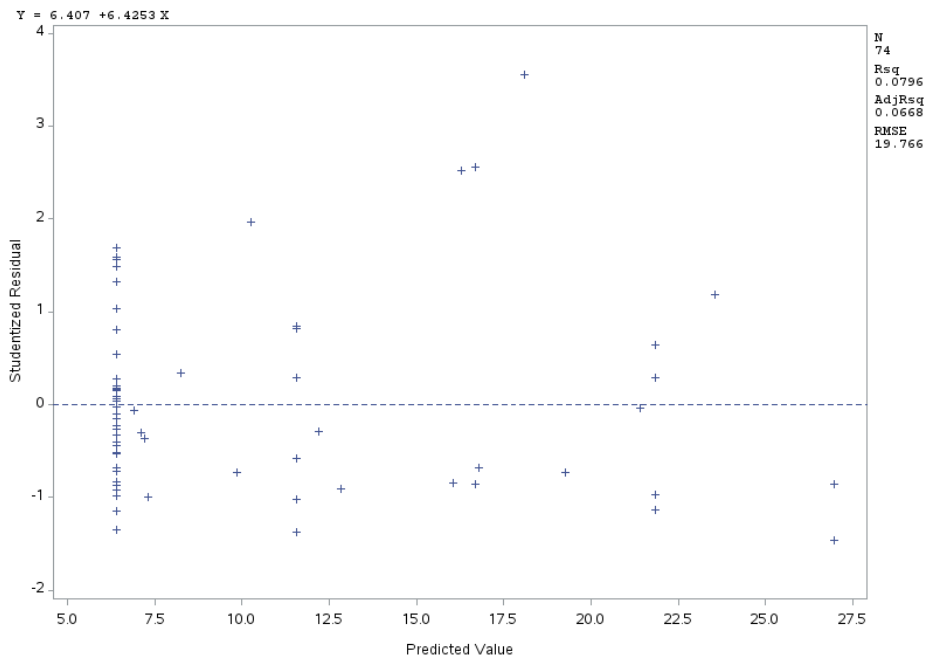
Figure 39. Residual plot of the Cost Overrun and Staffing Difficulty Regression Model
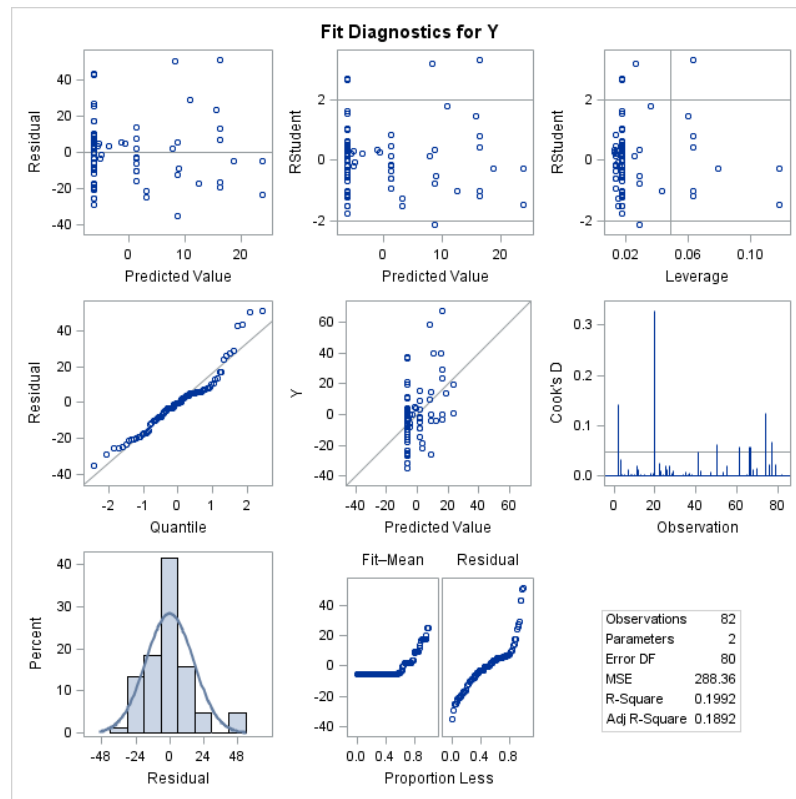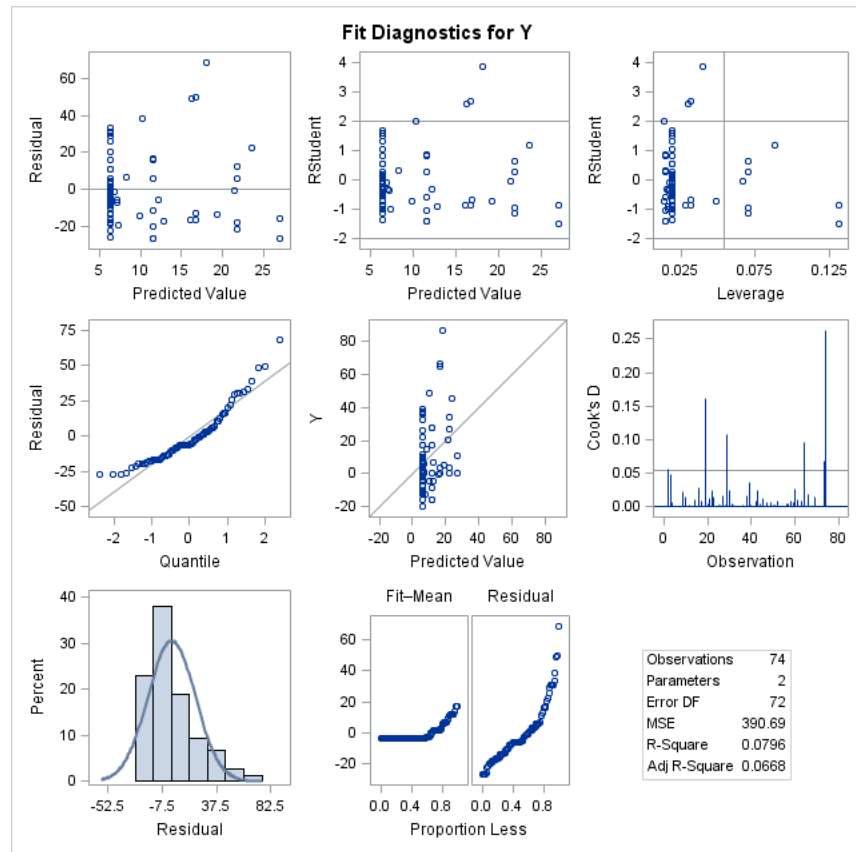

Figure 40. Residual plot of the Cost Overrun and Staffing Difficulty Regression Model

The influential outliers in this analysis also have been detected by checking if Studentized Residual exceeding 2.5 and then excluded from our analysis. Most of the outliers are projects with more than 100% cost overrun.

Linear Regression Analysis of the Relationship between Schedule Overrun and Staffing Difficulty

Total number of projects used in this analysis is 74. Table No.39 shows the detail of Analysis of Variance for whole model and Table No.40 shows its Parameter Estimates analysis.

Table No 39 Analysis of Variance for whole regression model of relationship between Staffing Difficulty and Time Overrun in Construction project

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	2431.8969	2431.89698	6.22	0.0149
Error	72	28129	390.68529		
Corrected Total	73	30561			

Table No 40. Analysis of Parameter Estimate of the regression model of relationship between Staffing Difficulty and Time Overrun in Construction project

Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	6.40700	2.72421	2.35	0.0214
X	X	1	6.42526	2.57532	2.49	0.0149

The equation of the model is "Time overrun (%) = 6.4070 + 6.425× Staffing Difficulties" and the R-Square is 0.08. the model is significant at 0.01 level. Figures 4.41 illustrates this linear regression model with 95% Confidence Interval.
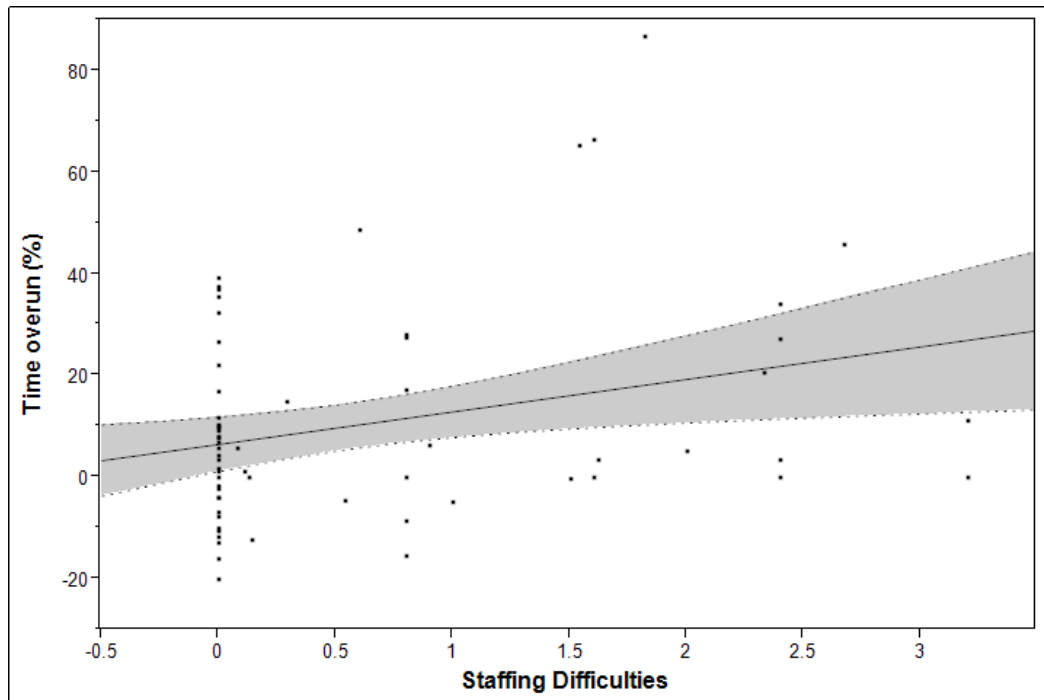
Figure 41. The regression model and its 95% CI of relationship between Staffing Difficulty and Time Overrun in Construction projects (number of projects used: 74)

Diagnostic Tests

To examine the reliability of models, diagnostic tests were performed on model. The residual plot of the models, shown in Fig. 42 demonstrates that residuals are randomly distributed in a band around the horizontal line of zero. The variance of error is also almost constant across the data. Therefore, it can be stated that the assumption of the homogeneity of variance is not violated and also errors are statistically independent in the model. The points in the plots of Figure 43 lie nearly along a straight line which indicates the error are distributed normally in the model.

Figure 42. Residual plot of the Time Overrun and Staffing Difficulty Regression Model

Figure 43. Residual plot of the Time Overrun and Staffing Difficulty Regression Model

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The influential outliers in database also have been detected by checking if Studentized Residual exceeding 2.5 and then excluded from our analysis. Most of the outliers are projects with more than 80% Time Overrun.

Poisson Regression Analysis of the Relationship between Safety Performance (TRIR) and Staffing Difficulty in Construction Projects

Introduction

Within society and the environment, there are occurrences that response variables and their possible outcomes are counts in which an event count refers to the number of times it occurs. The value of these response variables are only the non-negative integers. Examples of these variables are the number of car accidents that happen in a city per day or the number of insurance claims within a given period of time. The Poisson probability model, which is in the exponential dispersion family, is often used for a simulation model of these kinds of variables that occur randomly over time or at particular rate (Agresti 2015).

Therefore, accidents occur in the construction project can be simulated with this probability model. Chua and Goh (2005) argued that Poisson distribution is suitable for modeling construction incident occurrence. Glazner et al (1999) used Poisson regression analysis to examine the association between contract injury rates and contract safety practices. Bailer et al (1997) also used Poisson regression analysis to model fatal injury rates of workers in Agriculture, Forestry and Fishing.

The safety performance parameter used in this study is TRIR which is OSHA total number of accidents per 200,000 work hours. Chua and Goh (2005) argued that occurrence of event needs not to be measured in the time unit necessarily and it can be counted in any continuum such as space or man-hour working time. Tutz (2012) mentioned that the

Poisson distribution is the derivation of binominal distribution where the number of trails increase and the probability of success decreases accordingly. For these small intervals, then, the success can be defined as one occurrence of desired event. Since it is reasonable assumption in construction project that man-hour parameter can be partitioned into n small equal subintervals in which one accident at most can be happened, we can use Poisson distribution for modeling TRIR (Chua and Goh, 2005). Another assumption of the Poisson distribution is that the observations are independent from each other (Agresti, 2015). Since the TRIR in a construction project does not reasonably influence the TRIR on other projects, this assumption is also satisfied. In Poisson distribution, although in most cases there is an upper limit for the actual response, in the modeling, there is no upper limit on the values that may be observed (McCullagh and Nelder, 1983). This situation is similar to the actual situation of accidents occurrences in construction projects. The mass function of probability in this model is defined as:

$$P(y, \mu) = e^{-\mu} \mu^y / y! \qquad \text{for } y = 0, 1, 2,....$$

in which the mean (μ), variance and all other cumulants of Y are equal (McCullagh and Nelder 1983).

$$E(y) = var(y) = \mu \qquad \mu > 0$$

The Poisson Regression Model is the standard model for count data in which n independent observations (y_i, x_i) are assumed to be Poisson-distributed with mean μ_i (Tutz, 2012). The log-linear model of Poisson distribution is the most common model which uses log link to connect the mean to the linear predictor variable (Agresti 2015). The equation of the model is as:

$$\text{Log } \mu_i = \sum \beta_j x_{ij} \quad \text{for } j=1, 2, ...p$$

which also can be shown as:

$$Log\ (\mu) = x'\beta$$

Poisson Log-linear Regression Model

The independent variable of the regression model is the Staffing Difficulty Score in projects which was explained in section 4.4 and shown in Table 4.8. The response variable is the OSHA number of recordable incident cases per 200,000 work hour in construction projects (TRIR). The total number of data points is 50. The Software used for the analysis is SAS 9.3 using the GENMOD procedure. Table 41 shows the criteria for assessing goodness of fit of the model and Table 4.42 shows the result of analysis of parameter estimate of the model.

Table 4.41. Criteria for Assessing Goodness of Fit of Poisson Regression model between

Criteria For Assessing Goodness Of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	48	40.3547	0.8407
Scaled Deviance	48	40.3547	0.8407
Pearson Chi-Square	48	44.1251	0.9193
Scaled Pearson X2	48	44.1251	0.9193
Log Likelihood		-35.6711	
Full Log Likelihood		-38.9315	
AIC (smaller is better)		81.8629	
AICC (smaller is better)		82.1182	
BIC (smaller is better)		85.6870	

Table 42. Analysis of Parameter Estimate of the Poisson regression model

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	-1.3559	0.3198	-1.9827	-0.7291	17.98	**<.0001**
X	1	0.5198	0.1825	0.1620	0.8775	8.11	**0.0044**
Scale	0	1.0000	0.0000	1.0000	1.0000		

The equation of the model is as:

$$\widehat{Y}(x) = \widehat{\mu}(x) = e^{0.52X-1.36}$$

In which:

$\widehat{Y}(x) = \widehat{\mu}(x) =$ Estimated TRIR

X = Level of Staffing Difficulty (0-4)

As shows in Table 4.42, the model is statistically significant at 0.01 level (P-value= 0.0044). The Intercept parameter is also statistically significant at 0.0001 level. Figure 4.44 shows the graph of this Poisson Regression Model which illustrates the impact of craft labor staffing difficulty on construction safety performance parameter of TRIR.
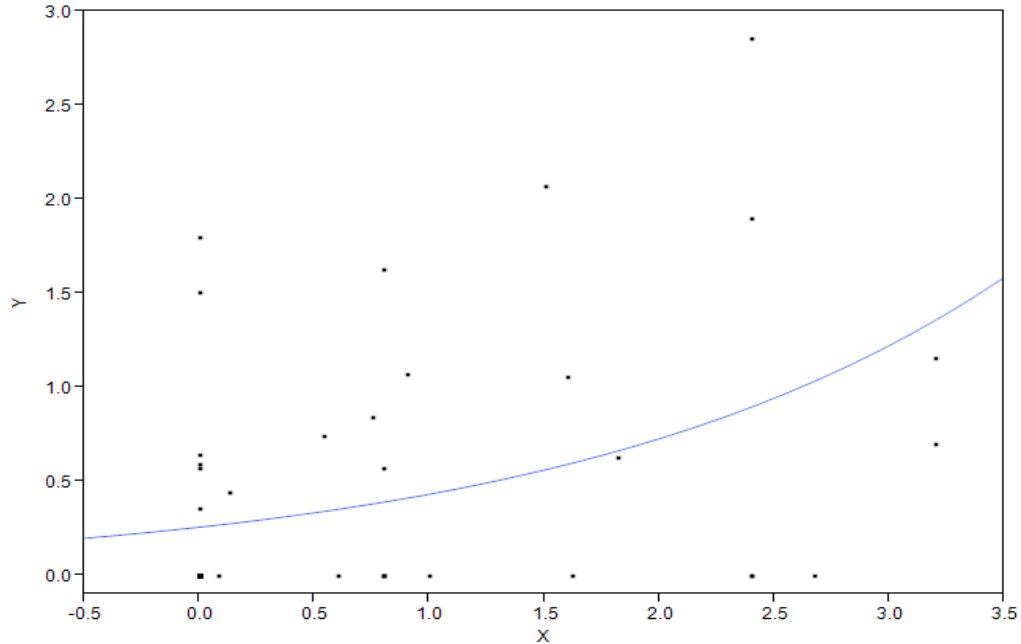
Figure 44. Poisson regression model for TRIR and Staffing Difficulty (50 Projects)

Y=TRIR, X=Staffing Difficulty

Goodness of Fit Test

The deviance which compares the log-likelihood of the fitted values for any observation to the log-likelihood of the perfect fit is the measure of discrepancy between the fit model and data (Tutz, 2012). If the model with log-link contains an intercept term, the deviance equal (Tutz 2012, Agresti 2015):

$$D = 2 \sum y_i \, log \left(\frac{y_i}{\hat{\mu}_i} \right)$$

Another alternative for assessing the goodness of fit of Poisson regression model is the Pearson Statistics which equal (Tutz 2012, Agresti 2015):

$$X_P^2 = \sum \left(\frac{y_i - \hat{\mu}_i}{\hat{\mu}_i} \right)^2$$

For fixed number of n and increasing mean unboundedly ($\mu_i \to \infty$), both D and X_P^2 have and approximately chi-squared (X^2) - distributed with N–P degree of freedom where p is the

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dimension of the parameter vector (Agresti, 2015). In our model, the n=50 and p=2, therefore DF=48. Table 4.43 shows the result of Chi-square test for goodness of fit of our model. Since the result of test is not statistically significant, we cannot reject null hypothesis which indicates that the data are consistent with a Poisson distribution. Therefore, we can conclude that the model fits reasonably well.

Table 4.43. Goodness of Fit of Poisson Regression Model

Goodness of Fit Statistic	Chi Square	DF	Prob >Chi Sq
Pearson	44.1278	48	0.6322
Deviance	40.3777	48	0.7747

Dispersion Test

The main feature of Poisson distribution is that the mean (μ) is equal to variance. In the following equation, the σ^2 which is called the dispersion parameter of Poisson model is assumed constant (McCullagh and Nelder 1983).

$$Var\ (Y_i) = \sigma^2 E(Y_i) = \mu_i$$

If the dispersion parameter(σ^2) is more than one, it means the conditional variance exceed the conditional mean and there is Over-dispersion in the model and if $\sigma^2 < 1$, a model is Under-dispersion (Tutz, 2012). McCullagh and Nelder (1983) argued that the dispersion parameter can be estimated by following equation:

$$\sigma^2 = X_P^2/\ (N - P) = \sum \left(\frac{y_i - \hat{\mu}_i}{\hat{\mu}_i}\right)^2 /(N - P)$$

in which X_P^2 is Pearson Chi-Square, N is total number of data points and P is dimension of the parameter vector. As shown in Table 4.41, $X_P^2 / (N - P)$ is equal 0.92 which is close to 1 and indicates that the model is not overdispersed or underdispersed.

Studentized Deviance Residuals

Examining residuals of the model helps us to find where our Generalized Linear Model is fitted poorly and where unusual observation occurs (Agresti, 2015). The plot of Studentized Deviance Residual versus Predicted Response Variable (Y) is illustrated in Figure 4.45. The plot shows no pattern and all points are scattered randomly around the zero line. Moreover, there is no unusual observation in the residuals which indicates that there is no outlier in the data points.
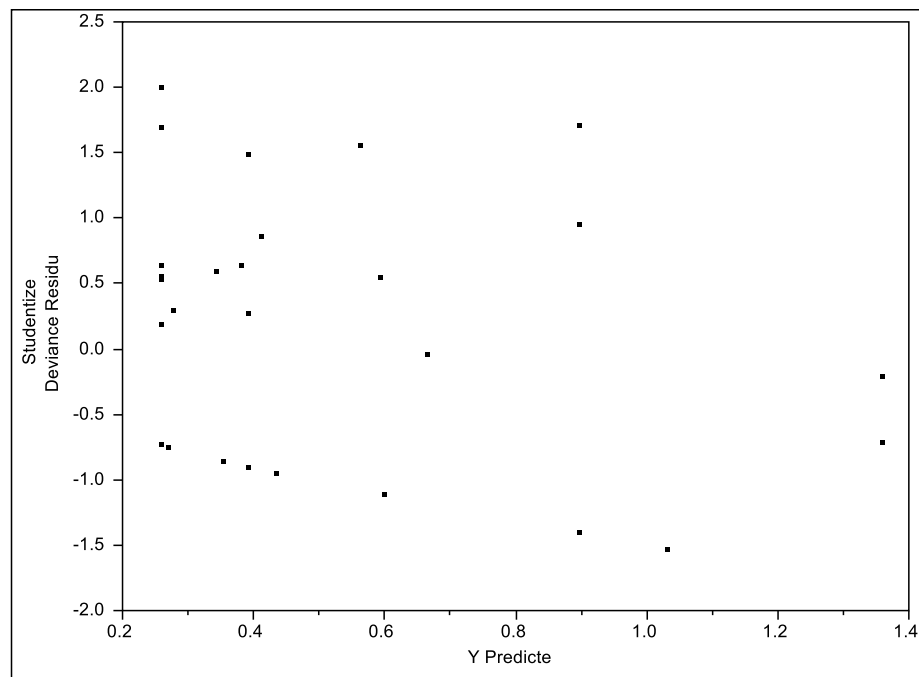
Figure 45. Studentized Deviance Residual by Predicted

95% Confidence Interval for Estimated TRIR

As mentioned before, in Poisson distribution, all cumulants of Y are equal to μ. McCullagh and Nelder (1983) argued that if all cumulants are O (n) and n tending to infinity, then

$$(Y - \mu)/ k_2^{1/2} \sim N(0,1) + O_p\ (n^{-1/2})$$

in which k_2 is the second cumulants of Y and is equal to μ. Since n=50, the part of $O_p\ (n^{-1/2})$ become very small and will be disregarded. Therefore we reach to the following:

$$(Y - \mu)/ \mu^{1/2} \sim N(0,1)$$

Hence the Y can be estimated with the normal distribution that has variance of μ ($\sigma^2 = \widehat{\mu}(x)$).

$$Y \sim N\ (\widehat{\mu}(x),\ \widehat{\mu}(x))$$

The 95% Confidence Interval for the response variable can be calculated as:

$$95\%\ \text{Confidence Interval} = \widehat{\mu}(x) \pm 1.96\sqrt{\widehat{\mu}(x)}$$

Table 4.44 shows the upper and lower bound of 95% confidence Interval of estimated TRIR for each level of staffing difficulty. Since the lower bound of 95% Confidence Interval for all Y is negative and negative value for our response variable is meaningless, we change all lower bounds with negative value to zero. It also should be noted that because there is no project with staffing difficulty score more than 3.2, we cannot provide estimation of TRIR for Very Severe Staffing Difficulty (score=4) condition.

Table 44. Expected TRIR with 95% Confidence Interval

Staffing Difficulty	Expected TRIR	Upper 95% Confident Interval	Lower 95% Confident Interval
0	0.26	1.25	-0.74 (0)
1	0.43	1.72	-0.86 (0)
2	0.73	2.39	-0.94 (0)
3	1.22	3.39	-0.94 (0)

The Figure 4.46 illustrates the regression model with its 95% confidence interval.
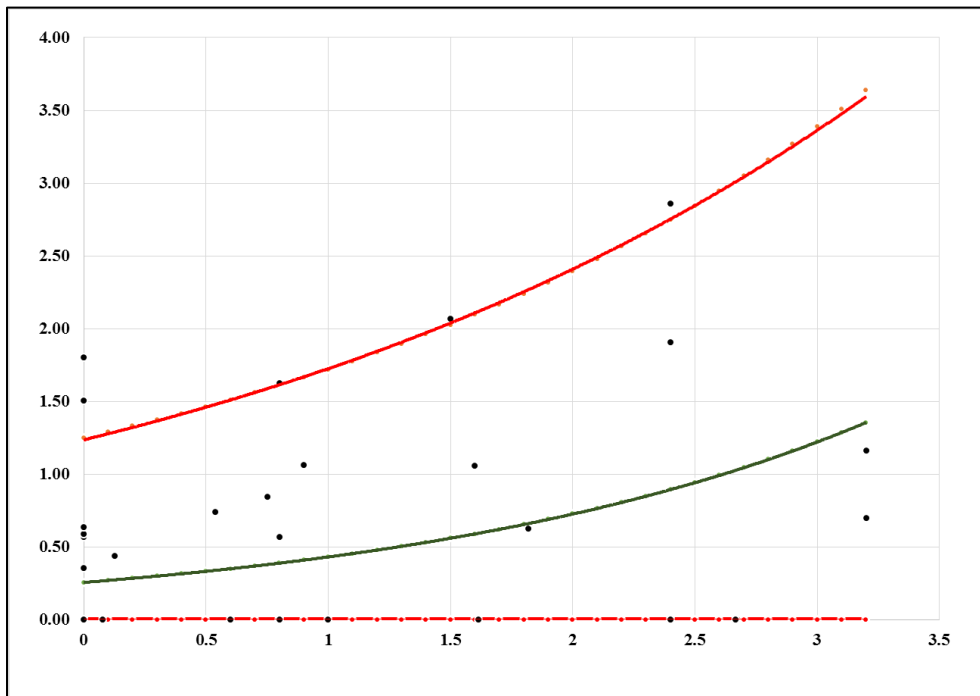
Figure 46. Poisson regression model of TRIR and Staffing Difficulty with 95% Confidence Interval

Model Validation:

To test validity of each model, about 18% of total number of projects in each model were selected randomly and excluded from regression analysis. The predicted values of new models were compared to the actual values of those excluded projects and then the mean absolute error (MAE) for each model is calculated. Table 4.45 shows the result of this analysis.

Table 45. The Mean Absolute Error (MAE) of Models

Model	Total number of projects in database	Number of projects randomly excluded	Number of projects used for new model	MAE
Cost Overrun	82	15	67	10.61
Time Overrun	74	13	61	15.76
Safety Performance	50	9	41	0.41

The mean absolute error for Cost Overrun Model is 10.61 which means, on average, the model predicts cost overrun with about 10 unit error. The MAE for Time Overrun Model is 15.76 and 0.41 for Safety performance model. Regarding the range of 95% Confidence Interval provided for each model, these errors are expected as they falls within their 95CIs of most the prediction values in all there models.

Sensitivity Analysis for Assigned Scores

As discussed earlier, Agresti and Finlay (2009) argued that when one assigns scores to the categorical variable, it is necessary to conduct Sensitivity Analysis to make sure the conclusion of the analysis would not differ significantly if other scales of score are chosen. In order to test this point, different scales of score were assigned to each five levels of staffing difficulty in RT-318 Survey. The score of this variable in CII BM&M database also adjusted to the new scale in each test. Then the result of new models' estimation was

compared to the main model's one. Table 4.46 shows different assigned score scales and also the explanation of the result for each test.

Table 46. Sensitivity Analysis of Models to different assigned score scale to staffing difficulty

Level	No difficulty	Slight	Moderate	Severe	Very Severe	Comment
Main Score	0	1	2	3	4	-
New Score Scale (1)	0	2	4	6	8	The results in the Cost Overrun and Time Overrun model are as same as the main model one. The result of Safety model in No difficulty and Slight level is similar to the main model but the result in Moderate and Severe level, in average, is 0.48 Unit less than main model prediction.
New Score Scale (2)	0	1	3	7	14	In the Slight, Moderate and Severe level, on average, the new models predict Cost Overrun 8 Units less and Time Overrun 6 Units less. These models predict almost similar to main models in No difficulty and Very Severe level. The result of Safety model in No difficulty and Slight level is similar to the main model but the result in Moderate and Severe level, on average, is 0.56 Unit less than main model prediction.

New Score Scale (3)	0	1	3	6	10	In the Slight, Moderate and Severe level, on average, the new models predict Cost Overrun 5 Units less, Time Overrun 4 Units less. These models predict almost similar to the main model in No difficulty and Very Severe level. The result of Safety model in No difficulty and Slight level is similar to the main model but the result in Moderate and Severe level, on average, is 0.51 Unit less than main model prediction.
New Score Scale (4)	0	3	5	9	16	In the Moderate and Severe level, on average, the new models predict Cost Overrun 6 Units less, Time Overrun 5 Units less. These models predict almost similar to main model in No difficulty, Slight and Very Severe level. The result of Safety model in No difficulty and Slight level is similar to the main model but the result in Moderate and Severe level, on average, is 0.60 Unit less than main model prediction.

The result of sensitivity analysis shows that the Cost Overrun and Time Overrun models are slightly sensitive to the extreme score scaling assigned to the staffing difficulty variable. All new models' predictions are slightly less than main models' ones in Slight, Moderate and Severe levels on overage of 6 Units less in Cost Overrun and 5 Units less in Schedule Overrun. However, in Very Severe and No Difficulty level, there is no difference between new models and main model. The Safety Performance model also is slightly

sensitive to these new extreme score scales in Moderate and Severe level with average of 0.54 Unit less in prediction comparing to the main model's one. This model has almost similar result with main model in No Difficulty and Slight Level of Staffing Difficulty.

In conclusion, since new models with new score scales demonstrate same patterns of result with slight deviation even if there is extreme score scale and this deviation is just in some level of staffing difficulty levels, we can state that the estimations of new models are not different significantly from main model's one and therefore all three models are considered reliable.

Discussion

Three regression models quantify the impact of craft labor shortage on construction project performances. They demonstrate the higher staffing difficulty in construction projects results in higher Cost Overrun, Schedule Overrun and TRIR. This result is also consistent with the comparison analysis provided in section 4.6 which shows that there is significant difference in performances of projects of Cost Overrun, Time Overrun and TRIR when projects experienced skilled craft shortage.

The first linear regression model demonstrates the statistically significant, at 0.0001 level, relationship between Cost Overrun and Staffing Difficulty. It shows that with increase in levels of staffing difficulty from 0 to 4, there is 9.41 Unit increase in percentage of Cost Overrun. The 95% confidence Interval for this estimate is (5.27, 13.55) and the R-square of model is 0.2. The combination of low P-value and low R-Square illustrates the situation in which the relationship is statistically significant but the model explains partially the variability of the response variable around its mean. This situation is completely consistent

with the nature of construction projects in which the cost overrun can be influenced by different factors other than craft labor shortage. However, to find the accuracy of prediction of the model and for more convenient use of its practical application, we will provide the 95% Confidence Interval for response value predictions of Cost Overrun for each level of staffing difficulty in the next section.

The second model is the simple linear regression model that determines the statistically significant, at 0.01 level, relationship between Schedule Overrun and Staffing Difficulty in construction projects. The model shows that with increase in each level of staffing difficulty, there is 6.43 Unit increase in percentage of Schedule Overrun. The 95% Confidence Interval for this parameter estimate is (1.36, 11.43). The model has pretty low R-Square which is 0.08. Similar to Cost Overrun model, the model has low p-value and also low R-Square which again can be interpreted as a situation that the model shows the statistical significant impact of staffing difficulty on Schedule Overrun but it can explain partially variability of Schedule Overrun. Similar to previous model, again this model reflects the reality of Schedule performance in construction projects in which it can be affected by several difference factors other than craft labor staffing difficulty. The 95% Confidence Interval for response variable of schedule overrun for each level of staffing difficulty provided in the next section illustrates the level of accuracy of model prediction.

The last model is the Poisson Log-Linear Regression model that demonstrates the statistically significant, at 0.01 level, relationship between TRIR and Staffing Difficulty. The model has reasonably good fit to the observed variables and also passed all diagnostic tests. The model shows that with the increase in level of Staffing Difficulty in project, TRIR increases with exponential behavior. The difference of TRIR between No difficulty

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level and Slight level is 0.17 while the difference between Slight and Moderate is 0.3. This difference would be 0.49 between Moderate and Severe level. The growth in the rate of increase in TRIR when there is increase in shortage of craft labor demonstrates the significant impact of craft labor shortage on safety performance in construction project. The 95% Confidence Interval for TRIR of each level of staffing difficulty shows the accuracy and precision of model prediction.

7. Craft Risk Availability Forecasting Tool (CRAFT)

The Craft Risk Availability Forecasting Tool (CRAFT) provides project managers, estimators, and site management teams a process to model the risk that craft labor availability poses to a specific project's safety, cost, and schedule performance. However, it should be noted that the CRAFT is intended as a risk analysis tool and it is not suitable for use to set contingencies or to adjust project costs to account for workforce impacts on project budgets and schedules.

What also should be considered is that the database of this study is limited to the U.S. and Canadian industrial projects which have been completed between 2001 and 2014. The median actual cost of construction phase of projects is $41 million with the range of 0.5$ to $8549 million. The median schedule of projects is 622 calendar days with the range of 46 to 3131 days. Therefore, this risk tool is not valid for projects which fall outsides these characteristics.

Tables 4.47-49 shows the expected Cost Change, Schedule Change and TRIR with their 95% Confidence Interval under different staffing difficulty circumstances. For example, if project manager expects that there will be Moderate craft labor staffing difficulty in coming project, he/she should expect that the project has 12.6% Cost Overrun due to this shortage.

He/she can be 95% confident that this overrun would be between 5.5% to 19.6%. He/she also should expect that project will have 19.2% Time Overrun with 95% confidence that it will be between 10.6% to 27.9%. He/she also should expect that the project will have TRIR of 0.73 with 95% confidence that it will be less than 2.39.

Table 47. Expected Cost Change and its 95% CI under different staffing difficulty circumstances (CRAFT)

Craft Labor Staffing Difficulty		Expected Cost Change (%)	Lower 95%CI (%)	Upper 95%CI (%)
No difficulty	0	-6.22	-10.67	-1.76
Slight	1	3.19	-0.93	7.31
Moderate	2	12.61	5.53	19.63
Severe	3	22.02	11.20	32.83

Table 48. Expected Schedule Change and its 95% CI under different staffing difficulty circumstances (CRAFT)

Craft Labor Staffing Difficulty		Expected Schedule Change (%)	Lower 95%CI (%)	Upper 95%CI (%)
No difficulty	0	6.41	0.98	11.84
Slight	1	12.83	7.74	17.92
Moderate	2	19.26	10.60	27.92
Severe	3	25.68	12.39	38.98

Table 49. Expected OSHA Number of Recordable Incident Cases per 200,000 Work Hour and its 95% CI under different staffing difficulty circumstances (CRAFT)

Craft Labor Staffing Difficulty		OSHA Number of Recordable Incident Cases per 200,000 Work Hour	Lower 95%CI	Upper 95%CI
No difficulty	0	0.26	0	1.25
Slight	1	0.43	0	1.72
Moderate	2	0.73	0	2.39
Severe	3	1.22	0	3.39

Conclusions

The analysis of craft workforce information and project performance of total 97 construction projects in North America demonstrates the significant impact of craft labor shortage on construction project performance. The following points can be concluded from our analysis:

- The Cost Overrun, Schedule Overrun and Safety performances (TRIR) of construction projects can be affected significantly from craft labor shortage. The result of analysis shows that the average of cost overrun in projects experienced craft labor shortage is 200% more than that in projects with no craft labor shortage. The schedule overrun and TRIR in projects that experienced craft labor shortage are about 130% more than those in projects with no skilled workers shortage.

- The regression analysis demonstrates that there is linear relationship between each Cost Overrun and Schedule Overrun variable and Craft Labor Staffing Difficulty variable.

The Poisson Log-linear Regression Model also shows the exponential relationship between TRIR and Craft Labor Staffing Difficulty in construction projects. These regression models shows with increase in level of craft labor staffing difficulty, there is increase in cost overrun, schedule overrun and TRIR in construction project.

- The Craft Risk Availability Forecasting Tool (CRAFT) provides project managers, estimators, and site management teams a process to model the risk that craft labor availability poses to a specific project's safety, cost, and schedule performance. It is simple, statistically sound model which can be used as a baseline performance comparison to analyze the benefit of potential project labor risk mitigation strategies to address craft labor availability impact on cost, schedule and, in particular, safety performance.

- The analysis of workforce information of RT-318 Survey projects shows that currently the Pipe welder, Pipefitter, Structural welder, and Electrician are those trades with the highest level of staffing difficulty and also involvement of hiring less experienced or skilled personnel among all 13 trades. Among these trades, the Pipefitters and Structural welders also have the highest percentage of hourly wage change with more than 3% increase compared to planned wage. The Supervisor, Ironworker, and Boilermaker also are the trades which have more than 3% increase in hourly wage.

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