ABSTRACT


In this research, workflow reliability is defined as the extent to which a construction plan is an accurate forecast of future events. In other words, the difference between what was planned to get accomplished and what is actually completed. Because construction projects consist of a large number of interdependent tasks, having a highly-reliable workflow is important not only for the productivity of an individual task, but also for entire project performance. The primary goals for this research are to develop methods and predictive models to identify and measure information exchange effectiveness in planning meetings, to quantify and analyze the benefit and cost trade-off for developing a highly-reliable plan, and to develop recommendations to guide site managers on making-do decisions. Information theory was utilized to measure the amount of uncertainty reduction in the workflow reliability due to information gained in planning meetings. Game theory was used to develop a framework to quantify and demonstrate the benefit of subcontractors’ extra effort for highly-reliable planning. Factor analysis was used to compare the underlying structure of the causes for task starting time and duration delay in China and the U.S. The Mann–Whitey U test, Random Forest machine learning, and entropy-based decision tree were used to identify the most important factors influencing making-do decisions. This research fills in gaps in the body of knowledge pertaining to workflow reliability improvement in construction projects. There has been limited research on quantifying the benefit of subcontractors’ horizontal partnering in increasing their planning reliability. Little effort has been made to investigate the importance of constraints removal discussions with respect to the existing workflow reliability. It is still unclear whether delaying start time of activities that lack precondition readiness will result in
less duration delay. In addition to addressing gaps in the body of knowledge, this research has a broader impact on the construction community. It provides a framework and repeatable analytical methods to identify, prioritize, and direct management’s effort for increasing workflow reliability in construction projects.
Strategies and Predictive Models for Reducing Workflow Variability in Construction Production Systems

by
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DEDICATION

This work is dedicated to my wife, Shirin, who has lived through my stress, anxieties during the completion of this piece of work. Without her love, sacrifice, patience, and support during the past five years, this would not have been possible. This work is also dedicated to my grandmother, my parents, my brothers, and my in-law family. It is their unconditional love and support that have been driving me so far.
BIOGRAPHY

Ashtad Javanmardi is the second of four children born to Parvin and Shapur Javanmardi in Mumbai, India in 1984. He grew up in Tehran, the capital of Iran, and graduated from Firooz-Bahram High school in 2002. Ashtad received his B.S. degree in Civil Engineering from K. N. TOOSI University of Technology in 2007 and his M.S. degree in Construction Engineering and Management from Iran University of Science & Technology in 2011 in Tehran, Iran.

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CHAPTER 1. INTRODUCTION

1.1 Background and Need

Construction projects resemble complex production systems in which a network of activities needs to be performed by different subcontractors (Ghoddousi et al. 2013). In this research “subcontractors”, also known as “trades”, resemble production units who perform specialty production tasks.

Workflow is defined as “the movement of information and materials through a network of production units, each of which processes them before releasing to those downstream” (Ballard 2000). Previous researchers have shown that workflow variability, defined as the quality of nonuniformity and inconsistency in release of work from the upstream crews (Hopp and Spearman 2000; Javanmardi et al. 2018), declines the project performance in different aspects, such as cycle time (Ballard 1999; Howell et al. 2001), labor productivity (Thomas et al. 2002, 2003; Liu et al. 2011), cost (Ballard and Howell 1994), and schedule efficiency (González et al. 2009).

Workflow reliability is defined as the extent to which a construction plan is an accurate forecast of future events. Percent Plan Complete (PPC) is used as an indicator for workflow reliability (Ballard 2000). PPC is calculated by dividing the number of tasks 100% completed at the end of a plan period to those tasks planned at the beginning of that plan period (Ballard 2000; Ballard and Howell 2003; Liu et al. 2011; Hamzeh et al. 2015). Higher PPC indicates lower variability in the workflow. According to Ballard (1999, 2000), PPC values are highly variable and usually range from 30% to 70% with an average PPC of 54%, thus illustrating the extent of workflow variability in construction.
Workflow can be managed effectively by increasing workplan reliability through implementing better planning strategies (Ballard and Howell 1998; Ballard 2000; González et al. 2010; Javanmardi et al. 2016). Ballard (2000) argued that although planning is the primary method for organizing construction activities, Critical Path Method (CPM) planning strategies do not ensure the reliable movement of work between trades. Therefore, Ballard (2000) introduced Last Planner System (LPS®) as a production planning and control system in construction based on Lean production principles that aimed to improve the reliability of workflow. Instead of emphasizing deadlines, LPS® emphasizes removing constraints in the make-ready process to produce more highly reliable short-term workplans (Hamzeh et al. 2015; Javanmardi et al. 2018).

To execute activities during the execution phase of construction projects, subcontractors need to remove constraints such as labor availability, material availability, equipment availability, prerequisite work readiness, space availability, detailed design and working method availability, external conditions (i.e. weather), etc. (Koskela 1999). This process is called “constraints removal” (Koskela 1999; Koskela 2000) and it is usually performed on a weekly basis during the execution of construction projects.

Although there is a massive body of knowledge pertaining to improvement of construction workflow reliability, the following research questions remain unanswered:

1. What is a fair and incentivized solution to distribute the benefit of subcontractors’ cooperation in highly-reliable planning in order to promote and sustain future cooperation?
2. How can information gain and information exchange efficiency of constraints-removal discussion at planning meetings be measured? What is a systematic method of prioritizing constraints-removal discussions?
3. What are the similarities and differences between causes of task starting time and duration delay in China compared to the U.S.? How can international contractors prioritize the causes of delay to be targeted to get the “biggest bang for the buck” with respect to their project portfolio?

4. What are the critical preconditions for a “making-do” decision, where “making-do” refers to starting a construction task without having all constraints removed.

1.2 Research Objectives

The goals of the research effort are to develop methodologies and analytical models that can be used to improve construction workflow reliability. This research focuses on identifying the main causes of unreliable workflow and proposing strategies based on Lean construction principles to improve workplan reliability. The four research objectives are listed below.

Objective 1: To quantify the benefit of cooperation among subcontractors in increasing their planning reliability at an operational level of construction using several different, but common, incentive alternatives.

Although Highly-reliable Planning (HRP) reduces the variability in a production system resulting in significant benefits for the downstream subcontractors, it requires every subcontractor to put more time, cost, and effort into the planning stage, which may not be cost effective for upstream subcontractors. A simulation model was developed and integrated with a cost model that specifies the relationship between cost and workplan reliability (WPR) level. Examining several different benefit-allocation models, this research found that a contribution-based benefit-allocation (CBBA) model using a game theory framework provided the best
incentive-based approach for all subcontractors, compared to the “cost-sharing”, and “equal net-benefit sharing” models.

**Objective 2:** To examine weekly planning meetings of a largely self-performed highway project to identify resolution and prioritization of different types of constraints with respect to workflow reliability.

While removing constraints are important, it remains unclear which types of constraint should have the highest priority for discussion at weekly planning meetings to better manage the existing construction workflow. This research used a bridge construction project as a case study to collect detailed weekly meeting minutes of 18 weeks and production data of 475 construction activities. Information theory approach was used to develop a framework to measure the amount of uncertainty and information sharing among constraint discussions. A Chow-Liu tree was then developed to guide project managers on the optimum sequence for discussing constraints at meetings so meeting time will be spent efficiently on the most important items.

**Objective 3:** To identify differences between task starting times and duration delays in projects in China and the U.S and to compare the underlying factor structure responsible for those differences.

Delay in a task starting time or duration can negatively affect the reliability of workflow for downstream construction crews and can reduce their productivity. Due to the complexity of construction projects, there are numerous causes of delay, each with a different level of impact which makes delay-reduction a difficult task. The objective of this research was to identify the root causes and underlying factor structure for task starting time and duration delay in China and compare those factors with ones in the U.S. Forty-four individual causes of delay
were identified and divided into eight constraint categories identified by Koskela (2000) and Wambeke et al. (2011). A questionnaire survey was administered to laborers, mid-level managers, and high-level managers working in construction projects in QingDao, ShanDong province of China in order to collect data on the amount of delay respondents experienced in their projects. The top-five causes of task starting time and duration delay were identified in China and were compared to ones in the U.S. Factor analysis was used to identify the underlying structure of causes of delay in China. The magnitude of delay caused by each factor and their similarity to the U.S. factors were identified. This study developed strategies based on impact-dissimilarity metrics to help international construction companies in developing effective strategies to reduce delay across their project portfolio.

**Objective 4:** To estimate the extent to which project managers’ experience of delay contributes to their future making-do decisions in China and the U.S.

Making-do, a decision to start work despite knowing that preconditions are not fully ready, has been referred as a type of waste in construction projects (Koskela 2004). This research conducts two surveys, one in China and one in the U.S., to find if delaying starting time of activities pays off in the future (less duration delay). Further analysis was done to find the critical causes of delay and preconditions which help to explain making-do decisions and reduce uncertainty in the decision-making outcomes. The findings help project managers to understand the difference and rationale in making-do decisions and have more efficient collaboration and communication when working in projects located in a foreign country.

In order to achieve objective 1, a simulation model was developed to quantify the benefit of extra effort and cooperation in performing highly-reliable planning. For objective 2, a case study of a bridge construction project was conducted to quantify uncertainty and develop
a methodology to help improve planning efficiency with respect to workflow reliability as the project goes forward. For objectives 3 and 4, results from two surveys in China and U.S. were used to study the relationship between constraints, making-do, and task delays.

1.3 Organization of the Dissertation

Chapter 2 is published in ASCE Journal of Management in Engineering (Javanmardi et al. 2017). Chapter 3 was submitted to ASCE Journal of Construction Engineering and Management and is in the process of revision based on the first-round reviewers’ comments which are all positive. Chapters 4 and 5 are planned to be submitted for publication in peer-reviewed journals. Each of these chapters has its own introduction, methodology, and conclusions sections. Chapter 6 summarizes the findings, contributions, limitations and future work directions of this research. References of each chapter are listed as a whole, at the end of this dissertation.
CHAPTER 2. BENEFIT OF COOPERATION AMONG SUBCONTRACTORS IN PERFORMING HIGH-RELIABLE PLANNING

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2.1 Abstract

As construction projects get larger and more complex, subcontractors can benefit from cooperation and by forming an alliance, such as partnering. Previous studies have discussed the benefit of cooperation or partnering among subcontractors and between them and other project stakeholders. However, there has been limited research to quantify the benefit of cooperation among subcontractors in performing high-reliable planning (HRP). Therefore, the purpose of this paper is to quantify the benefit of cooperation among subcontractors in increasing their planning reliability at an operational level. Although HRP reduces the variability in a production system that significantly benefits the downstream subcontractors, it requires every subcontractor to put more time, cost, and effort into the planning stage, which may not be cost-effective for upstream subcontractors. To model the described situation, a simulation model (built by simulation software) was integrated with a cost model that identifies the relationship between cost and work-plan reliability (WPR) level. By utilizing different
benefit-allocation models and evaluating their solutions, the paper demonstrates that a
collection-based benefit-allocation (CBBA) model using a game theory framework can
provide the most acceptable and incentivizing solutions for the benefit-allocation problem.
This study contributes to the body of knowledge in lean construction by quantifying the benefit
of subcontractors’ cooperation in increasing their planning reliability.

2.2 Introduction

During the construction phase of a project, subcontractors have a tendency to focus
only on their own tasks and even sometimes work toward their own priorities without
considering how their work affects the rest of the subcontractors’ tasks and the whole project
outcome (Sacks and Harel 2006). However, because of existing interdependencies, any
variation in subcontractors’ work plan can be transferred from one task to the next and causes
cost overruns and project delays (Koskela and Howell 2001; Wambéke et al. 2011; Lindhard
2014). According to Matthews and Howell (2005), project team integration could be a
promising solution to this problem because it promotes cooperation among subcontractors and
motivates them to focus on project outcomes instead of individual outcomes. In this paper, the
term cooperation represents the situation in which subcontractors “engage with others in a
mutually beneficial activity” (Bowles and Gintis 2011).

To change the separation tendency, new integrated forms of agreement were introduced
in the construction literature based on the relational contracting (RC) theory (Rahman and
Kumaraswamy 2002, 2004; Lahdenperä 2012; Ke et al. 2015). RC creates an atmosphere based
on trust, mutual respect, and cooperation. It posits the idea that the relationship between parties
is the most critical aspect of the agreement (Harper 2014). In RC, the team jointly takes the
responsibility of completing the project and shares any achievements and failures based on the “pain-share, gain-share” mentality (Yeung et al. 2007).

Partnering is a good example of practicing RC whereby subcontractors build a relationship among themselves and with other project parties to maximize the effectiveness of each participant’s resources (CII 1991). In fact, partnering is a code of conduct, or a formal attempt, intended to create a nonadversarial culture among subcontractors in which they can work together cooperatively, rather than competitively (Klee 2015). In this paper, no distinction was made between partnering and cooperation, and the terms are used interchangeably. As stated by Kumaraswamy and Matthews (2000), partnering between subcontractors could be limited to a single project based on a short-term agreement (project partnering) or could be extended over a series of projects based on long-term agreement (strategic partnering). Also, there are two different directions for subcontractors’ partnering: (1) vertical partnering [partnering with the general contractor (GC) or the client], and (2) horizontal partnering [partnering with other subcontractors (Asgari et al. 2014)]. Although various studies have considered the case of subcontractors’ partnering both in vertical (Love 1997; Kumaraswamy and Matthews 2000; Rahman and Kumaraswamy 2004; Hartmann and Caerteling 2010; Loosemore 2014) and horizontal (Perng et al. 2005; Asgari and Afshar 2008; Asgari et al. 2014) directions, few attempts have been made to quantify the benefit of subcontractors’ horizontal partnering in increasing their planning reliability. Therefore, the objective of this research is to demonstrate and analyze the benefit of cooperation among subcontractors quantitatively and accurately.

This paper studies a case of subcontractors’ horizontal partnering in which subcontractors are able to form a coalition and decide to increase their work-plan reliability
(WPR). The goal of this paper is to quantify the benefit of cooperation among subcontractors in increasing their planning reliability at an operational level. To this end, the authors examined benefit-allocation models by which subcontractors are able to distribute the future costs and benefits of high-reliable planning (HRP) among themselves in a fair and efficient manner. The desirable benefit-allocation model should find solutions that are both acceptable and incentivizing to all subcontractors and guarantee the sustainability of cooperation.

2.3 Literature Review

2.3.1 Work plan Reliability (WPR)

According to the lean-construction literature, a work plan consists of scheduled tasks that a subcontractor has planned to perform on site (operational level) in a short period according to the status of available resources and prerequisite tasks (González et al. 2010). A work plan is reliable when subcontractors do what they have planned to do (Alarcón 1997). The reliability of subcontractors’ work plan depends both on the subcontractors’ efforts and the efforts of their upstream subcontractors at the planning stage to create a high-reliable work plan. According to the last planner system (LPS) and the lean-construction literature (Ballard and Howell 1998; Ballard 2000) for improving work-plan reliability, a subcontractor needs to perform a constraint analysis on the planned activities to determine what needs to be done to make them ready to be executed. Meanwhile, the ability of a subcontractor to reliably perform the scheduled activities depends on the reliability of the so-called workflow in the production system (González et al. 2010). When the workflow is reliable, works are released reliably between subcontractors, and they can have a good estimation of the amount of work units or inventory buffer created by upstream subcontractors (Tommelein et al. 1999). Having a stable workflow requires the upstream subcontractors to increase their planning reliability (Ballard
and Howell 1998). Once the workflow is stabilized, substantial improvement in operations becomes possible, and potential gains in time and cost savings can be realized (Alarcón 1997). By investigating real construction project case studies, previous researchers have confirmed that improvement in subcontractors’ planning reliability will increase project performance (Thomas et al. 2003; González et al. 2007, 2008).

Considerable effort has been devoted to show the effect of WPR on project performance through simulation models. Tommelein et al. (1999) developed the Parade Game simulation model to illustrate the impact of workflow reliability on the performance of construction trades. The authors demonstrated that the reliability of the upstream trades significantly affects the downstream trades’ performance and proposed a question of whether the downstream trades should pay for the higher planning reliability of upstream trades. To extend the educational value of the Parade Game model, Alarcón and Ashley (1999) explored the impact of production strategies (selecting different sizes of buffers) on the project’s total time and cost. Recently, other researchers have developed the original Parade Game model to demonstrate the impact of managerial strategies (Han and Park 2011) and different types of task duration and activity sequences (Lindhard 2014) on workflow reliability. Javanmardi et al. (2016) identified the key trades of a single-line production system that highly contributed to reducing/increasing the project duration, total lost capacity, and total work-in-process (WIP) buffer. Although these papers demonstrated subcontractors’ WPRs affect their downstream subcontractors’ performance and the performance of whole project, a limited attempt has been made to quantify these effects and the extent to which each subcontractor contributes to the overall performance.
Improving WPR requires more time, cost, and effort in the planning stage (Hajifathalian 2011; Howell and Liu 2012; AbbasianHosseini et al. 2016). Increasing the degree of WPR by several subcontractors in a single production line does not necessarily result in increased benefit to all subcontractors. For example, HRP hardly increases the average productivity rate of the upstream subcontractors (Tommelein et al. 1999), and the savings due to the lower variation may not cover their additional cost in performing HRP. In contrast, some downstream subcontractors may experience significant benefits as a result of less variation in workflow due to upstream subcontractors performing HRP (Tommelein et al. 1999). This situation provides a loss of motivation for the upstream subcontractors to perform HRP unless all subcontractors agree on a pact to share the costs of HRP on that project and to distribute the benefits of HRP based on a predefined formula among themselves. Previous literature in the construction-management area has not thoroughly studied the possibility of subcontractors’ cooperation for increasing WPR and the associated beneficial opportunities. Also, to the best of the authors’ knowledge, there have been limited attempts to quantitatively allocate the benefit derived from HRP among cooperative subcontractors who commit to performing HRP.

2.3.2 Cooperative Game Theory

Game theory is a mathematical framework to study conflict and cooperation between intelligent, rational decision makers (von Neumann and Morgenstern 1944; Myerson 1991) in situations where one player’s decision may affect both the player and the other players’ outcome (Asgari and Afshar 2008). The result of the player’s decision or strategy behavior is called the player’s payoff or utility (Jackson 2008). According to Gilles (2010), there are two fundamentally different approaches to the description of an interactive decision situation. The
first is a noncooperative game theory, where players are concerned with their own interests and try to optimize their payoffs by selecting actions that are under their control. The noncooperative theory is based on the absence of any binding agreements between the decision makers. The second one is a cooperative game theory, where all players collectively pursue the maximization of the total wealth (benefit) that can be generated within the social decision situation at hand. In cooperative game theory, indeed, players can write a binding contract and determine how the generated benefit is going to be distributed among them.

In cooperative game theory, the focus is on what groups of players, rather than individual players, can achieve (Leyton-Brown and Shoham 2008). Previous studies have indicated the advantage of using cooperative game strategies over noncooperative strategies (He et al. 2016) and have stated that cooperative game strategies result in the expansion of the solution space and provide the opportunity for improving Pareto-optimal solutions (Madani 2011; Schreider et al. 2013). Using a cooperative game theory framework, Perng et al. (2005) demonstrated the potential benefits for formwork subcontractors collaborating in a coalition. Hsueh and Yan (2011) used cooperative game theory to allocate joint venture profits among its members based on their contributions. Asgari et al. (2014) suggested cooperative game theory as an appropriate framework for analyzing joint resource management in construction. The authors discussed how subcontractors can benefit considerably from joint resource management in construction projects. Based on partnering and cooperative game theories, He et al. (2016) demonstrated that the degree of willingness to cooperate (DWC) significantly influences cooperation gains, and incentives are effective in improving participants’ rewards.

Cooperative game theory provides an appropriate framework for studying subcontractors’ cooperation for increasing WPR through partnering. This is because
cooperative game theory in this paper assumes a transferable utility (TU) game in which (1) each coalition can be assigned a single value as its payoff, and (2) payoffs achieved from HRP can be freely reallocated among coalition members (Jackson 2008; Asgari et al. 2014). In this paper, a cooperative game with transferable utility resembles a pair \((N, v)\), where \(N\) represents all players (subcontractors) indexed by \(i\) in the grand coalition. \(v: 2^N \rightarrow \mathbb{R}\) is called characteristic function which assigns to each coalition \(S \subseteq N\) a real-valued payoff \(v(S)\) (also called coalition’s worth) that the players in that coalition can distribute among themselves (e.g., the total benefit of HRP). We assume that \(v(\emptyset) = 0\).

In the cooperative game theory, the allocation problem may be solved in a variety of ways, but according to the concept of core (Gillies 1959), an appropriate payoff vector \((i) = [x(1), x(2), \ldots, x(n)]\) should satisfy three criteria to be potentially acceptable by players and coalitions. These desirable criteria are efficiency, individual rationality and coalitional rationality as shown by following equations (Asgari et al. 2013; Ferguson 2014):

\[
\sum_{i \in N} x(i) = v(N) \quad (2.1)
\]

\[
x(i) \geq v(i), \quad \forall \ i \in N \quad (2.2)
\]

\[
\sum_{i \in S} x(i) \geq v(S), \quad \forall \ S \in N \quad (2.3)
\]

In the Equation (2.1), the efficiency principle requires the total value of the grand coalition, \(v(N)\), to be fully divided among players. The individual rationality principle in the Equation (2.2), will be satisfied when the payoff allocated to any player, \(x(i)\), under the grand coalition is greater than the amount that the player can attain individually, \(v(i)\). In the Equation (2.3), the coalitional rationality principle requires that the sum of payoffs allocated to the
coalition of players $S$, $\sum_{i \in S} x(i) = x(S)$, under the grand coalition to be at least as much as they could earn on their own.

### 2.4 Method

The research design includes five phases in 10 steps, as shown in Figure 2.1. First, a simulation model is developed, and basic assumptions of the model are described in the simulation model section. Then, to convert the simulation results to related costs, the relationships between the simulation model variables and the cost components are identified in the cost model section. To demonstrate the total benefit of HRP performed by all subcontractors in the project, subcontractors’ cost and benefit HRP is computed without considering cost and benefit sharing agreements and under the two extreme situations: (1) all subcontractors are performing low-reliable planning (LRP) (LLLLLLLL), and (2) all subcontractors are performing HRP (HHHHHHHH). Next, to distribute the total benefit of HRP, two traditional benefit-allocation models (cost-sharing model and equal net benefit sharing model) are used. These models allocate incremental benefits to the subcontractors based on their gross benefit and their equal contribution assumption, respectively. Finally, to tackle the limitations of traditional models, the contribution-based benefit-allocation (CBBA) model is utilized based on cooperative game theory to allocate incremental benefits to the subcontractors based on their contribution to creating benefits (saving cost and saving time) in each possible coalition.
2.4.1 Simulation Model

Based on the Parade Game simulation (Tommelein et al. 1999), in this section, the authors simulate a single-line production system with seven subcontractors (Figure 2.2) by using the ARENA 14.00 simulation software. ARENA simulation software was selected for modeling due to both its flexibility in using ready-to-use constructs and its intuitive flowchart modeling methodology with no need of customized code or programming. Overall, ARENA makes it easier to model variability in timing, resource assignment, quantity, and flow (Abbasian-Hosseini et al. 2014). The project scope comprises a production of 100 work units, which requires their transfer from input to complete. It is assumed that each worker allocated
to the task by a subcontractor is able to finish one unit of work per week. Also, all subcontractors have the same average production capacity (10 units/week), and production units completed by one subcontractor are prerequisites for the next subcontractor.

![Diagram of a single-line production system](image)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Create" /></td>
<td>Create</td>
<td>Creates entities (work-units).</td>
</tr>
<tr>
<td><img src="image" alt="Queue" /></td>
<td>Queue</td>
<td>Holding place (inventory buffer) for entities waiting to become involved in the succeeding activity.</td>
</tr>
<tr>
<td><img src="image" alt="Activity" /></td>
<td>Activity</td>
<td>Describes a certain type of work to be done and assigns process time to entities. The activity draws what is needed from the queue(s) that precede it.</td>
</tr>
<tr>
<td><img src="image" alt="Crew" /></td>
<td>Crew</td>
<td>Represents capacity (number of workers) that subcontractors allocate for performing their activity.</td>
</tr>
<tr>
<td><img src="image" alt="Dispose" /></td>
<td>Dispose</td>
<td>Disposes entities (work-units).</td>
</tr>
</tbody>
</table>

**Figure 2.2.** Single-line production system

To be able to capture the effect of subcontractors’ WPR on their subsequent time and cost of performing tasks, this study used a medium scenario as a benchmark and focused on two different levels in analysis: (1) LRP or L, and (2) HRP or H. For each degree of WPR, the simulation model assigns a predefined triangular probability distribution to the subcontractor’s production capacity (Figure 2.3). The probability density function of the triangular distribution is zero for values below the lower limit \(a\), and values above the upper limit \(b\). It is piecewise
linear rising from 0 at $a$ to $2/(b-a)$ at $c$ (peak value), then dropping down to 0 at $b$. The mean or average is $\mu = (a + b + c)/3$. Figure 2.3 shows that both LRP and HRP have the same average production capacity of 10 units/week. However, LRP distribution is associated with larger variability in comparison with the HRP.

![Figure 2.3. Triangular probability distribution related to production capacity in LRP and HRP](image)

The results presented in this paper are computed based on the average of 100 iterations (simulation runs) for each desired combination of $L$ and $H$. The simulation results are as follows: (1) project duration: the time (weeks) it takes for completing the project (the project starts at the beginning of Week 1, when the first subcontractor starts his or her task, and finishes at the end of Week $i$, when the last subcontractor completes his or her task); (2) subcontractors’ task duration: the time (weeks) it takes every subcontractor to complete his or her task (production of 100 work units); and (3) subcontractors’ total capacity allocated: total number of workers all subcontractors allocate to perform their tasks.

### 2.4.2 Cost Model

The author developed a cost model to analyze the impact of subcontractors’ different planning reliability strategies on their future cost. The model described here considers three cost components for calculating the total cost for each subcontractor: (1) direct cost, (2) indirect
cost, and (3) planning cost. Other components, such as rewards or penalties for timely completion or other costs, could be easily added for specific projects.

2.4.2.1 Direct Cost

Direct costs are those costs that can be easily associated with the production of one unit or with construction activity (Holland and Hobson 1999). In this study, the direct cost is proportional to the capacity (crews or workers) which subcontractors allocate to finish their planned tasks. In order to simplify, this study assumes a cost of $1 per capacity usage per week. However, this assumption does not impact the future results since they are proportional and will be presented in percentage. Therefore subcontractor i’s (Sub\textsubscript{i}) direct cost is:

\[ D_{i} = \text{Capacity allocated by Sub}_{i} \times 1 \]  

where \( D_{i} \) is the direct cost for the subcontractor \( i \).

2.4.2.2 Indirect Cost

According to the Palmer et al. (1999) an “indirect construction cost can be defined as a cost that can be identified with a construction project but not a specific unit of production.” Indirect construction costs contain 10% to 40% or more of the total cost and depend on the unique characteristics of a particular construction project (Becker et al. 2014). This paper assumes that the indirect cost for \( sub_{i}, I_{i} \), in each week is 30% of the total cost. Then the Equation (2.5) is derived as follows:

\[ I_{i} = 0.3 \times (I_{i} + D_{i}) \]  

By moving \( I_{i} \) to the left side of the equation, the indirect cost for the \( ith \) subcontractor is calculated as \( I_{i} = 0.43 D_{i} \).
2.4.2.3 Planning Cost

In this study, planning cost refers to the cost of production planning and control and not the project-level planning cost. Parties who perform the production planning need to investigate what needs to be done, break it down into tasks and figure out their optimal method and order, ensure that all prerequisites will be available, and assign each task to an operative or workstation (Koskela 2000). Previous researchers have considered the planning cost as part of the indirect cost (Becker 2012), and limited research has been conducted to investigate the relationship between the degree of WPR and the related planning cost. Abbasian-Hosseini et al. (2016), via a questionnaire-based survey, examined the relationship between the site managers’ efforts on on-site planning during construction and WPR, measured by the plan percentage complete (PPC). The survey was distributed to site managers of GCs and subcontractors in North Carolina. Analysis results of the 83 usable survey responses showed that those subcontractors with less effort (cost) spent on onsite planning have more variation in their weekly PPC ratio.

The current study assumes that in the typical situation (medium planning reliability), the cost of planning for the \(i\)th subcontractor \((P_{im})\) will be almost 7% of the subcontractor’s total cost. Also, LRP cost \((P_{il})\) and HRP costs \((P_{ih})\) will be 67% and 121% of \(P_{im}\) respectively.

Using Equation (2.5) the relation between planning cost and the direct cost is:

\[
P_{im} = 0.07 \times (I_i + D_i) = 0.07 \times (0.43 D_i + D_i) = 0.1 D_i
\]  
(2.6)

\[
P_{il} = 0.67 \times P_{im} = 0.67 \times 0.1 D_i = 0.067 D_i
\]  
(2.7)

\[
P_{ih} = 1.21 \times P_{im} = 1.21 \times 0.1 D_i = 0.121 D_i
\]  
(2.8)

2.4.2.4 Total Cost

The total cost of \(i\)th subcontractor \((C_i)\) can be calculated as follow:
\[ C_i = D_i + (I_i - P_{im}) + (1 - x_i)P_{it} + x_iP_{ih} \]  

(2.9)

The second term in the above equation, \((I_i - P_{im})\), corresponds to any other indirect costs of subcontractor \(i\) excluding their planning cost. Thus, with this formulation, planning cost will be included once in the calculation of total cost. In the Equation (2.9), \(x_i\) is decision variable and it equals to one if \(Sub_i\) does HRP, otherwise it’s zero.

2.4.3 Subcontractors’ Cost Metrics Performing HRP

Return on investment (ROI) is one of many ways to evaluate proposed investments because it compares the potential net benefit from an investment to its corresponding costs. Feibel (2003) calculated ROI by taking a ratio of benefit received as a result of an investment over the price of the investment and then multiplying it by 100 to establish a percentage that can be used as an indicator of performance (Equation (2.10)).

\[
ROI = \frac{\text{Net Benefit from Investment}}{\text{Cost of Investment}} \times 100 = \frac{\text{Net Benefit from HRP}}{\text{Additional Cost of HRP}} \times 100 \]  

(2.10)

When applied to reliable planning, calculating the ROI as a ratio of net benefit from HRP to the additional cost of HRP is suggested, because the potential savings resulting from HRP are considered benefits to subcontractors.

2.4.3.1 Cost of HRP

Cost of HRP is the cost of extra effort which \(ith\) subcontractor should spend to increase the reliability of his or her planning.

\[
\text{Cost of HRP for } Sub_i = P_{ih} - P_{it} \]  

(2.11)

2.4.3.2 Net Benefit from HRP

Net benefit from HRP of \(ith\) subcontractor is their gain from HRP (gross benefit) minus their cost of HRP.
\[ \text{Net benefit of HRP for Sub}_i = \text{Gross benefit of HRP for Sub}_i - \text{Cost of HRP for Sub}_i \quad (2.12) \]

The first part in Equation (2.12), \textit{gross benefit}, is the benefit before considering the planning cost. Practically, it can be obtained from two different sources: (1) future cost savings, which the subcontractor makes because of lower variation in the workflow (reduction in waste); and (2) any possible reward the subcontractor receives from the GC because of early completion of the subproject.

This study uses another definition for the net benefit of HRP. The net benefit for the \( i \)th subcontractor is the difference of the total cost in the two situations: total cost when performing LRP (\( C_{il} \)), and total cost when performing HRP (\( C_{ih} \)). By this definition and using Equation (2.12), Equation (2.13) can be written as follows:

\[ \text{Net benefit of HRP for Sub}_i = C_{il} - C_{ih} \quad (2.13) \]

To promote cooperation or partnering among subcontractors, the subcontractors who put themselves at disadvantage for the benefit of others should end up with higher payoffs that outweigh the costs of the disadvantage. Therefore, it is important to distribute the benefits of cooperation in a fair and efficient manner among the partners. If some partners perceive they are being treated unfairly, and distribution seems inequitable to them, the level of commitment by the disadvantaged partners will diminish and the partnering results will be affected (Kumar and Nti 1998). Although there are difficulties associated with choosing these methods from the outset, this choice appears essential to encourage partners to collaborate and bring key knowledge to the project and to increase the project’s probability of success (Segrestin 2006).
are performing HRP) is not only because of the subcontractor’s investment in performing HRP. Actually, the bigger portion of the subcontractor’s benefit comes from the upstream subcontractors’ investments in performing HRP. This makes a benefit allocation problem hard because the benefit of a subcontractor’s investment does not reflect in his or her own benefit, and instead, it reflects in the downstream subcontractors’ benefits. For this reason, it is necessary to investigate benefit-allocation methods that consider benefit and cost sharing among the subcontractors.

2.4.4 Traditional Benefit-Allocation Models

In the following benefit-allocation models, subcontractors are considered as a team and not individually. They have agreed to increase their WPR to prevent future lost capacity and work extension so that they can achieve more benefits through saving and minimizing waste. For a better understanding of procedures in upcoming models, the reader can assume a common pool from which the subcontractors can borrow money to pay for the additional effort needed for improving their WPR. At the end, subcontractors should return the borrowed money to the common pool based on their predefined rule of dividing the total benefit and the total cost of HRP among themselves.

2.4.4.1 Cost-Sharing Model

In this scenario, subcontractors will pay a part of the total HRP cost based on the incremental gross benefit they could make as a result of team effort in performing HRP.

Therefore, the cost of HRP for Subᵢ can be calculated as follows:

\[
\text{Cost of HRP for } Subᵢ = \frac{\text{Gross Benefit of HRP for } Subᵢ}{\text{Total Gross Benefit from HRP}} \times \text{Total Cost of HRP} \quad (2.14)
\]
The amount calculated by the previous formula is the \( i \)th subcontractor’s part of the total HRP cost, and the subcontractor should pay this amount back to the common pool. Consequently, the net benefit can be calculated using Equation (2.12).

### 2.4.4.2 Equal Net Benefit Sharing Model

In this scenario, the subcontractors pay for the HRP cost as a team and divide the net benefit equally among themselves. As a result, the net benefit for the \( i \)th subcontractor in this model is:

\[
Net \ Benefit \ of \ Sub_i = \frac{Total \ Net \ Benefit}{Total \ Number \ of \ Subcontractors} \tag{2.15}
\]

This method is based on the “egalitarian allocation rule”, which considers the same contribution of subcontractors in creating the total benefit.

### 2.4.5 Contribution-Based Benefit Allocation (CBBA) Model

In this benefit-allocation model, net benefits (payoffs) for subcontractors are determined using game theory and Shapley-value notation on fairness. The Shapley value is an important topic in cooperative game theory. It is the expected marginal amount contributed by a player to a coalition (Shapley 1953). This method identifies each player’s degree of importance in creating the overall cooperation result (total benefit) and the payoff the player should reasonably expect (Forgó et al. 1999). By using the Shapley value, the total benefit obtained after cooperation can be fairly distributed among the coalition members (Owen 2013), and the distribution is based on the four axioms of fairness defined by Shapley (Gilles 2010).

Shapley (1953) suggested that the average of the marginal contributions of Player \( i \) to all possible coalitions and sequences is the fair and efficient allocation to this player:
\[ x(i) = \frac{1}{|N|!} \sum_{S \subseteq N/\{i\}} |S|!(|N| - |S| - 1)! \left[ v(S \cup i) - v(S) \right] \]  

(2.16)

where \( x(i) \) is Shapley value of player \( i \), \( N \) is a finite set of players, indexed by \( i \); and \( |N| \) is the size of \( N \), \( S \) is subset \( S (S \subseteq N) \) represents a possible coalition of players. Therefore, \( S \subseteq N/\{i\} \) is possible coalition of players could be formed without having player \( i \) in them. \( v(S) \) is worth of coalition \( S \) that can be distributed among the coalition members. Similarly, \( v(S \cup i) \) is worth of a new coalition that has been formed by adding player \( i \) to the former coalition \( S \).

In this Equation (2.16), the Shapley-value of subcontractor \( i \), \( x(i) \), can be viewed as capturing the average marginal contribution of the subcontractor \( i \), where the average is over all the different sequences according to which the grand coalition could be built up from the empty coalition. If the subcontractor \( i \) is added to the set \( S \), the subcontractor’s contribution is \( [v(S \cup \{i\}) - v(S)] \). Now, multiply this quantity by the \( |S|! \) different ways the set \( S \) could have been formed prior to subcontractor \( i \)'s addition and by the \( (|N| - |S| - 1)! \) different ways the remaining subcontractors could be added afterward. Finally, sum over all possible sets \( S \) and obtain an average by dividing by \( |N|! \), the number of possible orderings of all the subcontractors.

In this study, the Shapley value for Sub\(_i\) is the benefit allocated to that subcontractor based on the average marginal amount the subcontractor contributes to every possible coalition he or she joins. To calculate the Shapley values for the current problem, the following steps should be followed:

1- Determine all the possible coalitions that could be formed by subcontractors for increasing the planning reliability. In this study, there are 127 \((2^7 - 1)\) different possible coalitions.
that can be formed by seven subcontractors, resembling every combination of low (L) and high (H) reliability. For example, the 126th coalition is consisted of six subcontractors \{S1, S2, S3, S4, S5, and S6\} performing HRP.

2- Determine the worth or value of each coalition: The value of a coalition is a real number that the coalition’s members can distribute among themselves. In the construction industry there are two well-known and unarguably valuable parameters, time and cost. In the problem stated in this paper, a coalition has a value if the members of that coalition by themselves could make some benefit (save cost) or save time through HRP; otherwise, the coalition’s value is zero. The developed simulation model and the cost model are used to identify the benefit and the time-saving by each of above combination of players. The amount of cost and time saved by each coalition is determined with comparing the cost and the time of that coalition in the situation that none of the subcontractors are performing HRP (LLLLLLL).

3- Identify the characteristic function of the problem (game). The characteristic function is a function that describes the amount of collective payoff a set of players can gain by forming a coalition. In this problem, the characteristic function contains a set \{v(1), v(2),..., v(127)\} with 127 elements and each element (calculated from the step 2) corresponds to its coalition.

4- Calculation of Shapley-values: Since the calculation of Shapley-values in this study consists of 7! (or 5040) permutation of \{S1, S2, S3, S4, S5, S6, S7\}, it could not be done without using a mathematical software. In this study MATLAB R2015b was used for coding the Shapley-value algorithm.
2.5 Analysis and Discussion of Results

2.5.1 Subcontractors’ Costs and Benefits of HRP (without Benefit and Cost Sharing)

To demonstrate the effect of WPR on subcontractors’ total cost, this study runs two different scenarios using the developed simulation model in this paper: (1) the situation when all subcontractors are performing LRP (LLLLLLL), and (2) the situation when all seven subcontractors are performing HRP (HHHHHHH). Total costs of subcontractors in these two situations are calculated based on the simulation results and the cost model introduced in the method section and are presented in Table 2.1.

<table>
<thead>
<tr>
<th>Subcontractor</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S4</th>
<th>S6</th>
<th>S7</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subs’ LRP Total Cost</td>
<td>141.45</td>
<td>154.46</td>
<td>158.42</td>
<td>161.94</td>
<td>165.89</td>
<td>170.43</td>
<td>172.27</td>
<td>1124.86</td>
</tr>
<tr>
<td>Subs’ HRP Total Cost</td>
<td>146.63</td>
<td>155.29</td>
<td>158.77</td>
<td>159.41</td>
<td>159.61</td>
<td>159.37</td>
<td>159.96</td>
<td>1099.04</td>
</tr>
<tr>
<td>Net Benefit of HRP</td>
<td>-5.18</td>
<td>-0.83</td>
<td>-0.35</td>
<td>2.53</td>
<td>6.28</td>
<td>11.06</td>
<td>12.31</td>
<td>25.80</td>
</tr>
<tr>
<td>Cost of HRP</td>
<td>5.58</td>
<td>5.80</td>
<td>5.92</td>
<td>5.93</td>
<td>5.93</td>
<td>5.93</td>
<td>5.94</td>
<td>41.03</td>
</tr>
<tr>
<td>Gross Benefit of HRP</td>
<td>0.40</td>
<td>4.97</td>
<td>5.57</td>
<td>8.46</td>
<td>12.20</td>
<td>16.99</td>
<td>18.25</td>
<td>66.85</td>
</tr>
<tr>
<td>ROI</td>
<td>-92.8%</td>
<td>-14.3%</td>
<td>-5.9%</td>
<td>42.7%</td>
<td>105.9%</td>
<td>186.5%</td>
<td>207.2%</td>
<td>62.9%</td>
</tr>
</tbody>
</table>

Figure 2.4 shows that, in the LLLLLLLL scenario, the LRP of upstream subcontractors increases the total costs of the downstream subcontractors, and the impact is more intense when approaching the end of the production line. The reason is that the downstream subcontractors experience more starvation due to lack of resources, and most of their allocated capacity remains idle during the execution of the project. In contrast, in the HRP situation, although the total costs for the first three subcontractors increase compared to the LRP situation (because of the additional planning cost), the downstream subcontractors achieve great benefits, and their total costs decrease. The results here are inconsistent with the findings of Tommelein et al. (1999). According to them, when variability in the production capacity of upstream
subcontractors decreases, downstream subcontractors experience less waste of their production capacity.

![Figure 2.4. Subcontractors’ LRP and HRP total cost without using cost and benefit sharing models](image)

This situation creates the following question (Tommelein et al. 1999): “Because upstream variation affects downstream performance, should downstream positions offer to pay for higher reliability upstream?” In construction projects, subcontractors will be more motivated to increase their WPR if they are assured of making future benefits for being reliable, either by other subcontractors or by the GC.

### 2.5.2 Traditional Benefit-Allocation Models

#### 2.5.2.1 Cost-Sharing Model

In this model, subcontractors make an agreement to share the total cost of HRP and are taxed based on the gross benefit they could make as a result of HRP. The cost of HRP for each subcontractor can be calculated using data from Table 2.1 and Equation (2.14). Consequently, by using Equation (2.12) and by subtracting the cost of HRP from the gross benefit, it is
possible to find the incremental net benefit of each subcontractor performing HRP. Table 2.2 shows that both the net benefit and the cost of HRP increase when moving from the first subcontractor to the last one. One can interpret that the downstream subcontractors invest in high reliability of upstream ones and receive some additional benefit (saving) from HRP of upstream subcontractors.

<table>
<thead>
<tr>
<th>Subcontractors</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>Total</th>
</tr>
</thead>
<tbody>
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<td>4.97</td>
<td>5.57</td>
<td>8.46</td>
<td>12.21</td>
<td>16.99</td>
<td>18.25</td>
<td>66.85</td>
</tr>
<tr>
<td>Gross Benefit (Percentage)</td>
<td>0.6%</td>
<td>7.4%</td>
<td>8.3%</td>
<td>12.7%</td>
<td>18.3%</td>
<td>25.4%</td>
<td>27.3%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Cost of HRP</td>
<td>0.25</td>
<td>3.05</td>
<td>3.42</td>
<td>5.19</td>
<td>7.49</td>
<td>10.43</td>
<td>11.20</td>
<td>41.03</td>
</tr>
<tr>
<td>Net Benefit of HRP</td>
<td>0.15</td>
<td>1.92</td>
<td>2.15</td>
<td>3.27</td>
<td>4.72</td>
<td>6.56</td>
<td>7.05</td>
<td>25.82</td>
</tr>
<tr>
<td>Net Benefit (Percentage)</td>
<td>0.6%</td>
<td>7.4%</td>
<td>8.3%</td>
<td>12.7%</td>
<td>18.3%</td>
<td>25.4%</td>
<td>27.3%</td>
<td>100.0%</td>
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<tr>
<td>Subs’ LRP Total Cost</td>
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<td>165.89</td>
<td>170.43</td>
<td>172.27</td>
<td>1124.86</td>
</tr>
<tr>
<td>Subs’ HRP Total Cost</td>
<td>141.30</td>
<td>152.54</td>
<td>156.27</td>
<td>158.67</td>
<td>161.17</td>
<td>163.87</td>
<td>165.22</td>
<td>1099.04</td>
</tr>
<tr>
<td>ROI</td>
<td>62.9%</td>
<td>62.9%</td>
<td>62.9%</td>
<td>62.9%</td>
<td>62.9%</td>
<td>62.9%</td>
<td>62.9%</td>
<td>62.9%</td>
</tr>
</tbody>
</table>

Using the cost-sharing model results in equal ROI for all subcontractors. Equal ROI implies that the future total benefit of HRP will not be shared equally between subcontractors. Rather, subcontractors share the total benefit based on the amount they invested. This increases subcontractors’ motivation in investing in HRP in case their ROI from HRP is greater than their ROI from the project. To evaluate the stability and fairness of current allocation solutions, the paper considers a situation in which the first subcontractor, S1, decides not to cooperate with the others and does not improve his or her reliability because the distribution of the total benefit using the cost-sharing model seems unfair to him or her.
Figure 2.5 shows that, when S1 is not doing HRP, although the subcontractor will achieve $0.15 less benefit than before, other subcontractors’ benefit will decrease much more ($9.05 totally) compared to S1. According to the game theory literature, it could be said that the current benefit allocation model is not stable because it leads to an increased bargaining power of S1. This subcontractor can potentially use this power to threaten the other subcontractors with leaving the grand coalition unless the subcontractor receives a higher share.

2.5.2.2 Equal Net Benefit Sharing Model

In this model, the net benefit of HRP is divided among subcontractors in an equal manner. The net benefit of the $i$th subcontractor using this method can be calculated using Equation (2.15) and by inserting $25.82$ as the total net benefit and dividing by the number of subcontractors. Also, the cost of HRP can be calculated using Equation (3.9) and by subtracting the net benefit from the gross benefit of HRP (Table 2.3).
Table 2.3. Subcontractors’ cost and benefit of HRP using equal net benefit sharing model

<table>
<thead>
<tr>
<th>Subs</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Benefit of HRP</td>
<td>0.40</td>
<td>4.97</td>
<td>5.57</td>
<td>8.46</td>
<td>12.21</td>
<td>16.99</td>
<td>18.25</td>
<td>66.85</td>
</tr>
<tr>
<td>Net Benefit of HRP</td>
<td>3.69</td>
<td>3.69</td>
<td>3.69</td>
<td>3.69</td>
<td>3.69</td>
<td>3.69</td>
<td>3.69</td>
<td>25.82</td>
</tr>
<tr>
<td>Net Benefit (percentage)</td>
<td>14.3%</td>
<td>14.3%</td>
<td>14.3%</td>
<td>14.3%</td>
<td>14.3%</td>
<td>14.3%</td>
<td>14.3%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Cost of HRP</td>
<td>-3.29</td>
<td>1.28</td>
<td>1.88</td>
<td>4.77</td>
<td>8.52</td>
<td>13.3</td>
<td>14.56</td>
<td>41.03</td>
</tr>
<tr>
<td>Subs’ LRP Total Cost</td>
<td>141.45</td>
<td>154.46</td>
<td>158.42</td>
<td>161.94</td>
<td>165.89</td>
<td>170.43</td>
<td>172.27</td>
<td>1124.86</td>
</tr>
<tr>
<td>Subs’ HRP Total Cost</td>
<td>137.76</td>
<td>150.77</td>
<td>154.73</td>
<td>158.25</td>
<td>162.2</td>
<td>166.74</td>
<td>168.58</td>
<td>1099.04</td>
</tr>
<tr>
<td>ROI</td>
<td>Inf</td>
<td>288.3%</td>
<td>196.3%</td>
<td>77.4%</td>
<td>43.3%</td>
<td>27.7%</td>
<td>25.3%</td>
<td>62.9%</td>
</tr>
</tbody>
</table>

Table 2.3 shows that the cost of HRP for the first subcontractor is negative. One can interpret that the equal net benefit sharing model not only waives the additional HRP cost for the first subcontractor, but also reimburses the first subcontractor the amount of $3.29 for being reliable. Because the cost of HRP increases by moving to the end of the line, it is possible to interpret that downstream subcontractors have invested more in HRP of the team compared to the upstream ones.

The equal net benefit sharing model is based on the egalitarian allocation rule, which spreads the value of a coalition equitably among the players in the game regardless of their contribution in the game (Jackson 2003). The egalitarian allocation rule has good properties while having some drawbacks. One prominent characteristic is that the egalitarian allocation solutions result in Pareto-efficient coalition of subcontractors, which is in fact strongly stable.

A coalition is efficient if there is no other coalition that could allocate higher payoffs for all of its members (Jackson 2008). However, this allocation method has little chance to be accepted by all subcontractors when not all of them contribute the same in generating the whole value of the coalition, and certainly in this situation, different subcontractors may have different claims over the total value of the coalition. Also, this allocation method causes lack
of motivation among subcontractors because they know the total benefit will be divided among them in an equal manner at the end, regardless of their participation level in performing HRP.

2.5.3 CBBA Model

In this section, the authors utilize cooperative game theory concepts and Shapley-value notations of fairness to determine fair and efficient solutions for the discussed benefit-allocation problem. The advantage of the CBBA model over the previous models is that it can consider the different levels of participation by subcontractors and their contributions to creating value in every possible coalition. Based on these contributions, the model distributes the total net benefit of grand coalition among subcontractors. When subcontractors improve their WPR in a team, they not only contribute to achieving future total savings within the team, but also contribute to decreasing the total time of the subproject undertaken by the team, which is undoubtedly favorable for the GC, and the team may receive some rewards as a result. Although subcontractors contribute to increasing the total benefit in the both scenarios, their role and level of contribution may differ in creating the total benefit in each of the aforementioned scenarios and depend on how the value of a coalition is defined.

2.5.3.1 Distribution of Benefit Based on Cost Saving

The value of each coalition in this scenario is the total net benefit (savings) created by the members of that coalition, and they are able to distribute it among themselves. The value of all 127 coalitions in this study were calculated using both the developed simulation model and the cost model. The 127th coalition was the grand coalition, which consists all seven subcontractors in this example, and $25.82 is the net benefit resulting from HRP, which subcontractors could distribute among themselves. It should be mentioned that many coalitions’ values were equal to zero. Those were the coalitions in which the total cost of HRP
was greater than the total gross benefit that the members could achieve as a result of HRP. By having values corresponding to every possible coalition, it is possible to identify the characteristic function of the game and calculate the Shapley values using the MATLAB code.

In the CBBA model, the Shapley values are the net benefits allocated to subcontractors. The results are shown in Table 2.4. Using the net benefit for each subcontractor and the gross benefits from Table 2.2, the cost of HRP can be calculated using Equation (2.12).

Table 2.4. Subcontractors’ cost and benefit of HRP using CBBA model (based on cost saving)

<table>
<thead>
<tr>
<th>Subs</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Benefit of HRP</td>
<td>2.96</td>
<td>4.32</td>
<td>3.61</td>
<td>3.22</td>
<td>3.48</td>
<td>4.46</td>
<td>3.77</td>
<td>25.82</td>
</tr>
<tr>
<td>Net Benefit (percentage)</td>
<td>11.5%</td>
<td>16.7%</td>
<td>14.0%</td>
<td>12.5%</td>
<td>13.5%</td>
<td>17.3%</td>
<td>14.6%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Cost of HRP</td>
<td>-2.56</td>
<td>0.65</td>
<td>1.96</td>
<td>5.24</td>
<td>8.73</td>
<td>12.53</td>
<td>14.48</td>
<td>41.03</td>
</tr>
<tr>
<td>Subs’ LRP Total Cost</td>
<td>141.45</td>
<td>154.46</td>
<td>158.42</td>
<td>161.94</td>
<td>165.89</td>
<td>170.43</td>
<td>172.27</td>
<td>1124.86</td>
</tr>
<tr>
<td>Subs’ HRP Total Cost</td>
<td>138.49</td>
<td>150.14</td>
<td>154.81</td>
<td>158.72</td>
<td>162.41</td>
<td>165.97</td>
<td>168.5</td>
<td>1099.04</td>
</tr>
<tr>
<td>ROI</td>
<td>Inf</td>
<td>664.6%</td>
<td>184.2%</td>
<td>61.5%</td>
<td>39.9%</td>
<td>35.6%</td>
<td>26.0%</td>
<td>62.9%</td>
</tr>
</tbody>
</table>

Table 4 shows that the CBBA model allocates more benefit to the most downstream subcontractor (S7) compared to the most upstream one (S1). This means that S7 has contributed more in creating the total benefit (savings) compared to S1. S7 contributes to the total cost savings by his or her presence in the team and by putting into effect the upstream subcontractors’ effort. Actually, S7 could save more as a result of others’ HRP and covers the main portion of the team’s HRP cost.

2.5.3.2 Distribution of Benefit Based on Time Saving

This scenario assumes that time is the most important element for the GC, and the reward which the team receives for the early completion of the subproject is much higher than their future cost savings within the team. Therefore, in this scenario, the value of a coalition is the time saved by its members, and the distribution of reward is based on subcontractors’
marginal contribution to decreasing the subproject time in every possible coalition. Based on this definition, the value of all 127 coalitions was calculated using the simulation model. The Shapley values for this game were calculated and are presented in Table 2.5. Here, the Shapley values show the time (days) that a subcontractor could save on average when the subcontractor joins every coalition of other subcontractors. In this scenario, the share of every subcontractor is equal to his or her contribution to saving time in the grand coalition.

Table 2.5. Subcontractors’ cost and benefit of HRP using CBBA model (based on time saving)

<table>
<thead>
<tr>
<th>Subs</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Saved</td>
<td>1.30</td>
<td>1.60</td>
<td>1.50</td>
<td>1.40</td>
<td>1.40</td>
<td>1.40</td>
<td>0.90</td>
<td>9.5</td>
</tr>
<tr>
<td>Time Saved (Percentage)</td>
<td>13.7%</td>
<td>16.8%</td>
<td>15.8%</td>
<td>14.7%</td>
<td>14.7%</td>
<td>14.7%</td>
<td>9.5%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Net Benefit (Percentage)</td>
<td>13.7%</td>
<td>16.8%</td>
<td>15.8%</td>
<td>14.7%</td>
<td>14.7%</td>
<td>14.7%</td>
<td>9.5%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

2.5.3.3 Distribution of Benefit Based on Time-Cost Trade-Off

Figure 2.6 shows the benefit allocation under the CBBA model considering the contribution of each subcontractor in saving time and cost during the project. This model gives cooperating subcontractors the possibility for a trade-off between time and cost and to implement their desired weight for distribution of the total benefit of HRP. For example, if time and cost receive the same degree of importance (future reward for early competition will be the same as the additional cost that will be saved by subcontractors) in the future partnering, the new distribution of net benefit will be the average of net benefit distributions in Tables 2.4 and 2.5.

The results shown in Figure 2.6 are consistent with the findings of the authors’ previous research. By utilizing Parade Game simulation framework, Javanmardi et al. (2016) found that the second subcontractor in a single-line production system contribute more than others in
reducing the project total time, total lost capacities and total inventory buffer by increasing his or her plan reliability.

Figure 2.6. Benefit allocation using CBBA model

2.6 Conclusion

To demonstrate the benefit of subcontractors partnering in increasing WPR in the operational levels of a project, this study generalized the original single-decision-maker Parade Game model to a multiple-decision-makers Parade Game model and showed that subcontractors’ horizontal partnering in performing HRP results in their incremental benefits. Several benefit-distribution models, including traditional models and the game theoretic CBBA model, were utilized to distribute the incremental benefits of HRP among cooperating subcontractors. By evaluating the results, the paper showed that traditional benefit-allocation models have some drawbacks and cannot be accepted as fair, efficient, and stable schemes for sharing the benefits of HRP. Therefore, the CBBA model was proposed as a fair and efficient model for distributing the incremental benefit of HRP.
Results from applying the suggested model to Parade Game simulation indicated that having more subcontractors in a team makes short-term partnering more valuable, and subcontractors can achieve more benefits based on HRP. However, those subcontractors, individually or in a smaller team, cannot achieve incremental benefits from HRP because the benefit of lower variability in the workflow does not cover the cost of HRP. Moreover, the CBBA model can identify the key subcontractors who contribute more than others in saving costs within the team and decreasing the time of the subproject. It can help both subcontractors and the GC to manage the team more efficiently by accommodating those subcontractors that contribute more than others to the success of project.

Building construction involves a large number of specialty trades typically working as subcontractors. They may be responsible for tasks in sequence, including foundation, steel erection, decking, formwork, concrete, drywall, mechanical, electrical, plumbing, roofing, glazing, vertical transportation systems, fire and sprinkler systems, and environmental controls. Highway and bridge construction projects also tend to include sequential tasks performed by various subcontractors, such as pile drilling, cap installation, deck assembling, and rail finishing. Although each task responsibility is performed by one subcontractor, every subcontractor can decide to devote a different amount of time and effort for planning. Therefore, performance of a subcontractor can impact the performance of direct and indirect successors and the entire project. The findings of this research can be applied in real-world scenarios as described earlier and provide a basis for subcontractors to evaluate the trade-off between extra planning effort and benefit to the subcontractors and the entire project. Consequently, the benefit can be fairly distributed among the subcontractors.
It should be stressed that the CBBA benefit-distribution model proposed in this paper is fully customizable depending on specific characteristics of the particular construction project, and parameters of models can be adjusted in the beginning stages during the development of the simulation model and cost model. However, modeling often differs from practice, as it always includes simplifying assumptions that should be considered when interpreting results (Madani 2013; Asgari et al. 2014). These simplifications, which can be addressed in future studies, include the following assumptions: (1) both LRP and HRP states have the same variability production capacity for all subcontractors; (2) all subcontractors have the same level of work concurrency and dependency, average productivity, direct cost, indirect cost, and medium reliability planning cost equation; (3) the same amount of effort is needed by each subcontractor to increase the degree of WPR from low to high; (4) the team’s cost for HRP is the summation of HRP costs when subcontractors plan individually; and (5) the problem is a TU game, and HRP’s cost and benefits for the team are equally valued by partnering subcontractors. In addition, this research also focuses on internal planning effort’s impact and subcontractors only. The impact from external factors, such as adverse weather or change order and the GC’s management strategies, is not included in the model. In this paper, the authors tried to demonstrate a real-world problem with a simple model, so it could be easily followed by practitioners and researchers. However, future studies may incorporate other factors into the model by removing the simplification assumptions one at a time. Future studies might, for example, add the effect of design changes by defining a random event (with a predefined probability) that affects (decreases) the productivity of subcontractors in some weeks. Also, future studies may investigate further by considering other aspects for improving WPR in a construction project (i.e., trust, social network and communication, transaction costs...
of cooperation) and a performing sensitivity analysis to evaluate the feasibility range for parameters that have been assumed in this study.
CHAPTER 3. IMPROVING EFFECTIVENESS OF CONSTRAINTS REMOVAL IN CONSTRUCTION PLANNING MEETINGS: AN INFORMATION-THEORETIC BASED APPROACH

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3.1 Abstract

Timely identification and removal of constraints is critical for improving workflow reliability. Construction project managers need to spend a significant amount of working time in various types of planning meetings to discuss, analyze, and remove constraints. However, the amount of uncertainty associated with each constraint, mutual information shared among constraints, and any information gained by addressing those constraints are not necessarily known with any great accuracy or precision. This research used a bridge construction project as a case study to collect empirical data on detailed weekly meeting minutes over 18 weeks, and the planned and actual starting and finish times of 475 activities. Information theory approach was used to develop a framework to measure the amount of uncertainty and information sharing among constraint discussions. A Chow-Liu tree was then developed to help project managers optimize the sequence of topics discussed so that meeting time may be spent more productively. Results from this particular study indicate that weekly planning
meetings need to strategically address “equipment availability”, “design and working method clarification”, and “prerequisite work readiness” issues since removing those constraints could improve workflow reliability by 5.6%, 4.9%, and 3.6% respectively. The contribution to the body of knowledge of this research was the development of a framework to utilize information-theoretic based approach to measure information exchange, uncertainty, and sharing in construction planning meetings. The method can be applied on other construction projects and the findings can help project managers plan and run meetings more effectively.

3.2 Introduction

Developing reliable workflow is critical for improving construction labor productivity. In order to make workflow reliable, construction project managers need to consider and remove at least seven constraints in planning meetings: design and working method, components and materials, laborers, equipment and tools, space, prerequisite work, and external conditions (Koskela 1999). Each of the seven constraints comes with a different level of uncertainty, which depends on various stakeholders’ capability and interaction. The constraints are also often correlated. It is not an easy task for project managers to evaluate and address the constraints in planning meetings effectively. The ever-changing dynamics and interaction on construction jobsites make the task even more difficult. In order to achieve the goal of reliable planning, construction site managers need to spend a significant amount of working time in planning meetings to communicate and negotiate with various stakeholders, including owners, residential engineering agents, designers, consultants, suppliers, manufacturers, local municipalities, and multiple subcontractors.

Although construction managers need to participate in planning meetings with various stakeholders routinely, there has been limited attention on quantifying the amount of
information exchange and consequently developing strategies to run planning meetings effectively to improve workflow reliability (Jang and Kim 2007, 2008; Lindhard and Wandahl 2011, 2012; Hamzeh et al. 2015, 2016; Wang et al. 2016). There are numerous alternatives for setting a meeting time frame, deciding on who should attend the meeting, choosing the meeting’s agenda and determining sequence (Schwartzman, 1989). Each of the decisions can make an important contribution to meeting effectiveness. Lacking a clear understanding on the mechanism of information gain and transmission in meeting process causes not only waste of time, but can also affect productivity losses.

This study examines information gain arising from constraints removal discussions at weekly planning meetings. The objectives are to 1) identify the importance of different types of constraints to workflow reliability, 2) quantify the effect of each constraint removal on improving workflow reliability, 3) develop an optimal order of addressing constraints at weekly planning meetings, and 4) measure information gain from constraint removal discussions to reduce uncertainty in workflow reliability. This study used information theory framework to quantify the amount of information generated and gained from constraints removal discussion in a bridge construction project. Information theory methods were used to provide a measure of information and mutual information gains between constraints removal discussions and workflow reliability improvements. This study selected a bridge project on the east coast of the U.S., with a budget of $250 million and a duration of 3 years. Empirical data was collected on detailed weekly meeting minutes over 18 weeks and planned and actual starting and finish times of 475 activities for pile, cap, girder, and deck installation. The findings will be helpful for project managers to improve planning meeting efficiency. Project managers will be able to prioritize meeting agenda based on the importance of constraints,
information sharing among constraints, and the amount of information gain from constraints discussions.

3.3 Literature Review

3.3.1 Constraints removal and Workflow Reliability

Workflow is the flow of work from one crew to the next, where the work output of a crew is the prerequisite to the work performed by the successor (Abbasian-Hosseini et al. 2017). Workflow is reliable when works are completed as planned. Plan Percent Complete (PPC) measures workflow reliability, calculated by dividing the number of tasks 100% completed at the end of a plan period to those tasks planned at the beginning of that plan period (Ballard 2000; Ballard and Howell 2003; Liu et al. 2011; Hamzeh et al. 2015). Koskela (1999) suggested considering removing seven constraints in planning meetings to improve PPC. They are unclear/unavailable construction design and specifications, unavailable components and materials, unavailable laborers, unavailable equipment, unavailable space, incomplete prerequisite works, and adverse external conditions. In addition to the seven constraints, Lindhard and Wandahl (2012) suggested two additional constraints namely “unsafe working conditions” and “unknown working conditions” to emphasize the national laws and problems that often occur during excavations or refurbishment activities. In this research, the seven constraints by Koskela (1999) and “unsafe working condition” from Lindhard and Wandahl (2012) were used for analysis because they have a comprehensive and thorough coverage of the issues considered and discussed for this project in the planning meetings.

Jang and Kim (2008) showed that there is a significant positive relationship between Percentage of Constraints Removal (PCR) and PPC based on data from two bridge construction projects. In a more recent study, through computer simulation and using Tasks Made Ready
(TMR) measurement, Hamzeh et al. (2015, 2016) showed identifying and eliminating constraints during the make ready process influence the reliability of construction lookahead plans and impact on project duration. Liu (et al. 2011) found a positive correlation between PPC and productivity on an oil refinery project.

While several studies have addressed constraints removal (Jang and Kim, 2007, 2008; Lindhard and Wandahl, 2012; Hamzeh et al., 2015, 2016), there has been a lack of research on the relative importance of the different types of constraints to workflow reliability. Limited research was found to quantitatively measure effectiveness of constraints removal discussions, amount of information shared among constraints, and information gain from constraints removal discussion during weekly planning meetings. To fill in the gap of knowledge, this research used an information theory approach to develop a framework to measure the amount of uncertainty and information sharing among constraint discussions. Based on the findings, a Chow-Liu tree was built to recommend the optimum sequence to discuss constraints in construction planning meetings for this type of project.

3.3.2 Meetings in Construction

Meetings play an important role in construction as they provide formal lines for communication in construction projects (Mincks and Johnston 2010). Regular site meetings between the different stakeholders on a project can facilitate decision-making and goal-setting, scheduling, solving problems, and information sharing (Gorse and Emmitt 2007, 2009). Gorse et al. (1999) explored a range of media including verbal communication, such as face-to-face meetings, to non-verbal communication, such as letter, fax and email. Their results showed that the former was perceived to be the most effective medium of communication within the construction industry. Gorse et al.’s findings were supported by Carlsson et al. (2001), who
conducted communication research within the Swedish construction industry. By studying two Design-Build and two Design-Bid-Build projects, Carlsson et al. found the most used method of communication was formal meetings, with 57% of all contacts being made during meetings. Their findings also revealed that construction projects with traditional fragmented delivery systems rely more on formal information exchange that takes place in structured, face-to-face meetings.

Chang and Shen (2013) categorized site meetings into three categories: (1) meetings with owner, (2) internal General Contractor (GC) meetings, and (3) meetings between GC and subcontractors. By surveying and interviewing 26 contractor engineers at three organizational levels in seven large projects, Chang and Shen found although contractors are satisfied with the contents and results of meetings, they believe meetings are less effectively used to coordinate works compared to other methods such as contract documents, plans/procedures, written correspondence, and site visits. Due to the large number of meetings held on the studied projects, however, the researchers could not find what proportion of meetings was useful for coordination purposes. Also, their research did not include recommendations to increase meetings’ effectiveness.

In another study, Van Gassel et al. (2014) analyzed 37 meetings during the product and production design phases of a prototype of an industrial and demountable building system to identify variables that influence collaborative working in design meetings. Using the non-parametric Mann–Whitney U test, the researchers found the variables “aim of meeting,” “control of meeting,” “participants,” “tools,” and “outcomes” are a suitable set to describe successful collaborative working in design meetings. The drawback of this research was that the meetings were viewed as “container or black box” and the content of the meetings was not
examined. This approach of meeting analysis disregards the meeting itself, and it is not clear: (1) what information is shared and discussed in meetings, (2) how efficiently information is discussed and transferred, and (3) how meeting participants behave and interact during meetings.

Grose and Emmitt (2007, 2009) have made a considerable effort to analyze interactions during construction meetings using the Bales interaction process analysis (IPA) method. In Grose and Emmitt (2007), the researchers collected data from 3 to 4 sequential progress meetings of 8 construction projects during their construction phase. They found the level of negative emotion and critical discussion in construction meetings was very high compared to what was observed in other work groups, which suggests problems do not pass unchallenged. In Grose and Emmitt (2009), by observing 30 progress meetings of 10 construction projects (3 meetings each) in the UK, they found socio-emotional interactions (or relationship building) during meetings in the projects completed within budget are significantly greater than in those completed over-budget.

To the best of the authors’ knowledge there has been limited effort to formally or numerically examine what information is shared and discussed in construction meetings and how useful this information is to the project outcomes. There is a need for developing methods that can extract information from construction meeting discussions and utilize that information to help construction managers in improving their meeting effectiveness during project.

3.3.3 Information Theory

Developed by Shannon (1948), Information theory is a complete theoretical framework to quantitatively measure the information (or uncertainty) content in a distribution of data values. In recent years, there has been an increasing trend in use of information theory in
various domains, including: visualization and optimization (Xu et al. 2010; Xu et al. 2017), medical science (Steimer et al. 2015; Blokh and Stambler 2017), bio-mechanics (Gazula et al. 2015), and civil engineering and construction (Xiao-me and Xiao-jun, 2011; Jalayer et al. 2012; Chang et al. 2017). In civil engineering and construction, information theory has been mainly used for risk and structural analysis. For example, Xiao-me and Xiao-jun (2011) applied entropy measurement methods to assess risks of a construction-agent system. Jalayer et al. (2012) used an information-theoretic based approach to compare several alternative scalar- and vector-valued intensity measures (IMs). To assess the constructability of truss structure systems, Chang et al. (2017) utilized information theory methodology combined with symmetry-group, Markov chain and Monte Carlo methods to quantify the amount of information needed to construct truss structural systems with different assemblies.

Given a random discrete variable X with a sequence of m possible outcomes \(x_i, x \in \{x_1, x_2, \ldots, x_m\}\), with probability of \(p(x_i)\) for the random variable X to have the outcome \(x_i\), the amount of information (or uncertainty) content for the random variable can be computed using Shannon’s entropy, \(H(X)\):

\[
H(X) = \sum_{i=1}^{m} p(x_i) \log_2 \frac{1}{p(x_i)} \text{bits}
\]  

(3.1)

In Equation (3.1), \(bit\) is a unit of information. Since entropy uses log base 2, the units are called bits (short for binary digits). The maximum entropy for a random variable \(X\) with two possible outcomes (i.e. a binary variable) is 1.00 bit, which occurs when there are equal numbers of observations for each of the two possible outcomes in the data set (or the two possible outcomes have equal chance (50% probability) of happening) (Kelleher 2015). The minimum entropy for a random variable \(X\) with two (or more) possible outcomes is 0 bits, which occurs when all the observations in data set have the same value for \(X\).
Entropy, $H(X)$, measures “the inherent uncertainty in $X$”, or “how much information is gained when an outcome of $X$ is observed” (Li and Vitanyi 1997; Stone, 2015). This entropy can then be used to quantify the dependency between two random variables $X$ and $Y$ (Shannon 1948; Cover and Thomas 2006). The mutual information, $I(X,Y)$, is the measure of information that can be learned from one set of data (i.e. $Y$) having knowledge of another set of data (i.e. $X$) (Abebe and Price, 2004), and can be defined by:

$$I(X,Y) = \sum_{i=1}^{m_x} \sum_{j=1}^{m_y} p(x_i, y_j) \log_2 \left( \frac{p(x_i, y_j)}{p(x_i)p(y_j)} \right) \text{bits}$$  \hspace{1cm} (3.2)

where $m_x$ (or $m_y$) represents the possible different values $X$ (or $Y$) can take each with probability $p(x_i)$ (or $p(y_j)$) and $p(x_i, y_j)$ is the joint probability of the $X$ and $Y$ variables. As can be deduced from Equation (3.2), the mutual information is a symmetric criterion, i.e. $I(X,Y) = I(Y,X)$. It can be shown from Equation (3.2) that mutual information can be equivalently rewritten as (Stone 2015):

$$I(X,Y) = H(X) + H(Y) - H(X,Y)$$  \hspace{1cm} (3.3)

with

$$H(X,Y) = \sum_{i=1}^{m_x} \sum_{j=1}^{m_y} p(x_i, y_j) \log_2 \left( \frac{1}{p(x_i, y_j)} \right) \text{bits}$$  \hspace{1cm} (3.4)

being the entropy of a joint distribution of $X$ and $Y$.

Chow and Liu (1968) introduced a simple graphical model, known as the Chow-Liu tree, for understanding the dependency or causal structure between a set of random variables (Gazula et al. 2015; Steimer et al. 2015). The graphical model was composed of nodes representing a set of random variables $S = (X_1, ..., X_n)$ and undirected links $\epsilon$ connecting pairs of these nodes. Chow and Liu (1968) proved that a tree constructed using the following
steps minimizes the information difference between the original data and the dependency tree.

A Chow-Liu tree can be created following the steps below (Jensen and Nielsen, 2007; Schaffernicht et al. 2007):

1. Calculate the mutual information $I(X_i, X_j)$ for each pair $(X_i, X_j)$.
2. Consider the complete I-weighted graph: the complete undirected graph over \{X, ..., X_n\}, where the links $(X_i, X_j)$ have the weight $I(X_i, X_j)$.
3. Build a maximal-weight spanning tree for the complete I-weighted graph.
4. Choose a variable as a root node.

A Chow-Liu tree provides an intuitive and user-friendly graphical model for prioritizing constraints removal discussions at weekly meetings. It allows project managers to realize how events or pieces of information are connected or lead to one another (Gazula et al. 2015).

3.4 Research Method

The research included four phases in ten steps, as shown in Figure 3.1. In the first phase, the case study project was selected and project background information was collected. The second phase focused on collecting empirical data on meeting minutes, look ahead plan, and budget and actual man-hours for 475 activities for 18 weeks. The authors calculated workflow reliability and analyzed the meeting minutes to obtain the frequency of constraints removal discussions. The third phase classified weekly workflow reliability into four groups, from high to low. Entropy of constraints removal discussion and their mutual information with workflow reliability were calculated. In the last phase, the research team identified the importance of constraints, quantified the improvement of workflow reliability from constraints removal discussion, determined the optimal order of constraints removal using Chow-Liu tree, and
measured information gain from constraint removal discussion to reduce uncertainty in workflow reliability.

3.4.1 Data Collection

3.4.1.1 Project Description

A bridge construction project in the United States was selected for the case study because its major activities, including pile, cap, girder, and deck installation, were linear and
repetitive, which made an ideal case for comparing effects of constraints removal on workflow reliability. The project is a Design-Build project with an estimated cost of $250 million. The project started in March 2016 and it is scheduled to be completed by September 2019. The project consists of a six-lane, 2.7-mile bridge with a maximum span length of 350 ft and a vertical clearance of 70 ft both on land and over ocean. The highly dynamic harsh marine environment proved to be one of the most challenging aspects of the project for both the designers and contractors. The design team divided the bridge into three "approaches" to accommodate the different geographic site conditions. The three approaches are South, Navigation, and North. This research focused on the 10 Bents (69-78) over the ocean of the North approach to have similar type of work, design complexity, and the same managers and crews for the duration of this study.

As shown in Figure 3.2, the North approach structure consisted of piles, pile caps, girders and decks. Each Bent has three piles driven 110 ft into the ground on average to prevent the potential issues with scour (sand washing away from around the piles). The piles were all precast concrete cylinders 54 in diameter and approximately 140 ft in length. After piles were driven, the pile cap crew cast pile caps in place. Afterward, precast girders were installed, followed by cast-in-place deck.
Figure 3.2. A Bent cross section

The Design-Builder of this project was a joint venture of a Designer and GC. The GC self-performed over 90% of the work because execution of the project activities required highly-trained and experienced staff and costly equipment which was the expertise of the GC. Therefore, the GC team was directly responsible for scheduling activities, providing labor, materials and equipment, and executing the work.

3.4.1.2 Weekly Planning Meetings

This project holds weekly planning meetings to plan and coordinate work on site. All weekly meetings covering Bent 69-78 were held on Wednesday mornings at 7:30 AM. The meetings lasted 90 minutes on average, with a minimum of 44 minutes and a maximum of 114 minutes. Participants varied from meeting to meeting. There were on average 12 people participating in these meetings, with a minimum of 7 and a maximum of 16. Participants included 1 senior construction manager, 1 construction manager, 1 project manager, 1 project control manager, 2 general superintendents, 3 crew superintendents, 3 project engineers, and 4 field engineers who attended more than 75% of the meetings. One of the authors of this paper
also actively participated in all meetings as the field engineer in charge of pile installation activities.

The objectives of weekly meetings were to keep all the project team members up to date on progress, provide them an opportunity to discuss their concerns, plan for future problems that may arise, and discuss other issues. The contents and discussions of all 18 meetings were recorded by the GC’s project engineer in meeting minutes. The project engineer had 7 years of experience working in infrastructure projects and was on board on this project from day one. Meeting minutes were descriptive and contained what had actually transpired during the meetings in detail. A typical agenda for the progress meetings contained the following items:

- Health, Safety, and Environmental: incidents and near miss incidents during past week, plans to prevent future incidents (i.e. safety inspection and job hazard identification), weather condition, required environmental permits and permit approvals.

- Quality: quality issues (such as crack appearance on casings, or not achieving the pile designed capacity in minimum tip), available solutions/alternatives for fixing the issues, sending Request for Information (RFI) to designer/owner, confirming solutions for fixing issues, and giving updates on the fixing progress.

- Schedule and Workflow: scheduling deliveries (materials and equipment), scheduling laborers, scheduling tasks and identifying schedule goals considering constructability, availability of labor/material, and equipment.

- Productivity: productivity evaluation of different crews (i.e. pile, cap, girder, deck installation crews), comparing to baseline productivity, reasons for low productivity, future remedies for increasing productivity.
• Operation: updates on procedures followed for executing tasks, reviewing RFIs, clarification on designs, specifications and execution methods, clarification on task sequences, and solving constructability issues.

• General Discussion: quotes, labor/equipment/material costs, contract terms and conditions, site management, maintenance of traffic, staff/subcontractors’ issues, and in general all the tasks required to run the project and do not fall in other categories.

3.4.1.3 Workflow Reliability

Workflow reliability was measured using PPC. In order to calculate PPC, the authors collected weekly lookahead plan updates for 20 weeks. The 20 weeks period covered the same 18 weeks as the meeting minutes did, plus one week before and one week after that period. In each week, the plan included detailed activities for pile, cap, girder, and deck installation. For example, the activities for pile installation were survey to find pin pile location, install templates, survey to find the pile gates, cut and weld pile gates, install casings, excavate casings, trip piles, initial drive piles, extract casings, final drive pile to minimal tips, and remove templates. The project schedule contained detailed records of planned and actual starting and finish time for each activity and was updated in the morning of each Friday. PPC was calculated based on the record of the weekly updated schedule.

3.4.2 Data Analysis

3.4.2.1 Classification of Meeting Minutes

Specific names and information (i.e. suppliers, subcontractors, and participants names) were removed before data analysis for confidentiality purpose and avoiding potential bias. The meeting minutes contained 801 words on average, with a minimum of 443 words and a maximum of 1199 words. After carefully reviewing the meeting minutes, the authors classified
the discussions into the eight constraint categories. Table 3.1 shows a sample classification of weekly meetings based on constraints removal categories. The description in the column (1), “Discussion Item” was extracted from the meeting minutes. One example in each of the eight constraints removal categories is listed in Table 3.1 and constraints are labeled in the second column. This classification was reviewed, corrected, and confirmed with project engineers who participated in all the meetings and worked on the project full time during the 18 weeks.

**Table 3.1. Sample classification of discussion items at weekly meetings based on constraints**

<table>
<thead>
<tr>
<th>Discussion Item (1)</th>
<th>Constraints Removal Category (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A working on environmental permit allowances, get w/ DOT. Plan may not be needed</td>
<td>External Condition (X₁)</td>
</tr>
<tr>
<td>with current pile driving methods that minimize jetting.</td>
<td>Equipment Availability (X₂)</td>
</tr>
<tr>
<td>Bent x – Pile 1 repair. Waiting on Crane 1200 repair, possibly by 9/8.</td>
<td>Labor Availability (X₃)</td>
</tr>
<tr>
<td>Engineers from the supplier company needed for 1st 54” cylinder pile on north</td>
<td>Material Availability (X₄)</td>
</tr>
<tr>
<td>approach in mid-May.</td>
<td>Pre-requisite Work Readiness (X₅)</td>
</tr>
<tr>
<td>2 of 3 pile have low 28 compressive strength and are not stamped by XXDOT.</td>
<td>Space Availability (X₆)</td>
</tr>
<tr>
<td>Wait for XXX to cancel delivery. Next delivery date is 8/31.</td>
<td>Design and Working Method clarification (X₇)</td>
</tr>
<tr>
<td>Trestle install needs to progress or 54” piling op will stop next week.</td>
<td>Safe Work Condition (X₈)</td>
</tr>
<tr>
<td>This crew needs to be dedicated to install and a separate crew for extraction;</td>
<td></td>
</tr>
<tr>
<td>possibly use X’s cap crew for extraction.</td>
<td></td>
</tr>
<tr>
<td>Install all three (3) casings, excavate, and set one (1) pile on the furthest</td>
<td></td>
</tr>
<tr>
<td>west side out of the way of the other piles.</td>
<td></td>
</tr>
<tr>
<td>How high can we leave north 54” pile template? Minimum pin pile embedment – 20’</td>
<td></td>
</tr>
<tr>
<td>Need to max out (minimizes casing vibro), makes access better, need to</td>
<td></td>
</tr>
<tr>
<td>excavate casing to EL -60’ in order to not jet.</td>
<td></td>
</tr>
<tr>
<td>Safety line for 66” OD casing – X and Y: Are we using mouse hole or fabricated</td>
<td></td>
</tr>
<tr>
<td>pad eye for safety line? Using mouse hole.</td>
<td></td>
</tr>
</tbody>
</table>
3.4.2.2 Classification of PPC

The purpose of the PPC classification is to convert PPC into a categorical variable so that mutual information can be calculated between PPC groups and constraint discussions. This study used the k-means clustering algorithm (Macqueen 1967) to classify PPC values into two groups (A and B). The MacQueen (1967) k-means clustering algorithm was selected for computing initial cluster seeds because it classifies data into different clusters based on the distribution characteristics and Euclidean distances among data points. In addition, it is a non-overlapping algorithm and observations will not be classified into more than one cluster (Linoff and Berry 2011). The detailed calculation steps are illustrated in Ibbs and Liu (2011). SAS Enterprise Miner (SAS EM) 14.2 was used to conduct the k-means analysis. The results are shown in Table 3.2.

Table 3.2 shows the clustering results. The results of classifying PPC values into two groups are ‘A’ and ‘B’. Group ‘A’ has an average PPC of 73% and includes PPCs that are higher or equal to 63% and lower and equal to 82%. Group ‘B’ has an average PPC of 46% and includes PPCs that are higher or equal to 31% and lower and equal to 57%.

<table>
<thead>
<tr>
<th>PPC Group</th>
<th>Average PPC</th>
<th>Number of Observations</th>
<th>PPC Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>73%</td>
<td>10</td>
<td>[63%, 82%]</td>
</tr>
<tr>
<td>B</td>
<td>46%</td>
<td>8</td>
<td>[31%, 57%]</td>
</tr>
</tbody>
</table>

3.4.2.3 Entropy and Mutual Information Calculation

Entropy $H(X)$, $H(Y)$, and $H(X, Y)$ were calculated in 6 steps. An example is used to illustrate the process.

1- The discussion items in each meeting were classified under eight constraint categories, from $X_1$ to $X_8$, as shown in the columns (2)–(9) in Table 3.4. The values are the
frequency with which each constraint was discussed in a meeting. Also, PPC values were classified into two groups using k-means clustering algorithm. The results are shown in the last column of Table 3.4.

2- Generate a cross-tabulation for $X_i$ ($i = 1, 2, 3, \ldots, 8$) and $Y$. For example, Table 3.3(a) is a cross-tabulation displaying in how many meetings “material availability” constraint was discussed once, twice, …, n-times under each PPC level (A or B). The first column of Table 3.3(a) shows that out of 18 meetings, there were two meetings when “material availability” constraint was not discussed and ended up having PPC at A (higher) level. There were two meetings when “material availability” was not discussed and ended up with a B-level (lower-level) PPC. There are in total eight cross-tabulations between $X_i$ and $Y$ pairs.

3- Calculate $p(x_i, y_j)$, the probability of having a meeting with certain frequency of constraint removal discussions and a particular PPC level. This was achieved by dividing all the values in Table 3.3(a) by 18. The results are shown in Table 3.3(b).

4- Calculate Shannon information $h(x_i, y_j)$ by taking logarithms to the base 2 of $1/p(x_i, y_j)$, as shown in the Equation (3.5). The results are shown in Table 3.3(c).

$$h(x_i, y_j) = \log_2 \left( \frac{1}{p(x_i, y_j)} \right) \tag{3.5}$$

5- Calculate joint entropy $H(X_4, Y)$ using Equation (3.17). This was done by multiplying matching cells in Table 3.3(b) and Table 3.3(c). The results are shown in Table 3.3(d) in the zone highlighted in grey. For example, $p(x_1, y_1)$ is 0.11 and $h(x_1, y_1)$ is 3.17. The product equals 0.35. $H(X_4, Y)$ is the summation of all values in the grey area. In this case, the joint entropy between “material availability” and PPC is 3.13.
6- Calculate marginal entropies for “material availability” constraint, H(X4), and PPC, H(Y), using Equation (3.1). For example, H(X4) of 2.26 is the summation of all the values in the last row of Table 3.3(d).

7- Calculate the mutual information using Equation (3.3) based on the results of steps 5 and 6. For example, the mutual information between X4 and Y, I(X4, Y), is: H(X4) + H(Y) – H(X4, Y) = 2.26 + 0.99 – 3.13 = 0.12. (shown in Table 3.5). Mutual information is the degree of association between two variables and measures how much knowing one of the two variables reduces the uncertainty about the other.

<table>
<thead>
<tr>
<th>X4 (Material Availability)</th>
<th>PPC</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

(a) X4×Y1 cross table

<table>
<thead>
<tr>
<th>X4 (Material Availability)</th>
<th>PPC</th>
<th>0.11</th>
<th>0.11</th>
<th>0.17</th>
<th>0.11</th>
<th>0.06</th>
<th>0.56</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.11</td>
<td>0.11</td>
<td>0.17</td>
<td>0.11</td>
<td>0.06</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.11</td>
<td>0.00</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>0.22</td>
<td>0.11</td>
<td>0.28</td>
<td>0.22</td>
<td>0.17</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

(b) Joint and marginal probabilities

<table>
<thead>
<tr>
<th>X4 (Material Availability)</th>
<th>PPC</th>
<th>0.35</th>
<th>0.35</th>
<th>0.43</th>
<th>0.35</th>
<th>0.23</th>
<th>0.47</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.35</td>
<td>0.35</td>
<td>0.43</td>
<td>0.35</td>
<td>0.23</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.35</td>
<td>0.00</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>0.48</td>
<td>0.35</td>
<td>0.51</td>
<td>0.48</td>
<td>0.43</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>

(c) Shannon information

Using the same methods, entropies of H(Xi), H(Y), and H(Xi,Y) were calculated for all eight constraints with two PPC categories. The results are shown in Table 3.5. The higher the value of entropy, the higher the level of the uncertainty associated with the variable. For example, if a variable only has one outcome, which means it is 100% certain, its entropy is 0 \( (H(X) = 0 \times \log_2 \frac{1}{0} + 1 \times \log_2 \frac{1}{1}) \). If a variable has two possible outcomes with equal probability of occurrence, then the entropy is 1 \( (H(X) = 0.5 \times \log_2 \frac{1}{0.5} + 0.5 \times \log_2 \frac{1}{0.5}) \).
Therefore, a discrete variable with higher entropy contains more uncertainty (or information) than a variable with lower entropy.

### 3.5 Results and Discussion

Table 3.4 was created using the instructions given in step 1 of the previous section. The table shows the frequency of discussions pertaining to each constraint category during the meeting conducted at that week along with the PPC of the following week. For example, the first row in Table 3.4 contains the frequency of discussions addressing pre-defined constraint categories at the week 1 meeting along with the PPC calculated for week 2.

**Table 3.4.** Constraints removal discussion and PPC group numbers

<table>
<thead>
<tr>
<th>Week</th>
<th>External Conditions (X₁)</th>
<th>Equipment Availability (X₂)</th>
<th>Labor Availability (X₃)</th>
<th>Material Availability (X₄)</th>
<th>Prerequisite Readiness (X₅)</th>
<th>Space Availability (X₆)</th>
<th>Design and W. Method (X₇)</th>
<th>Safe Condition (X₈)</th>
<th>PPC (Two Groups) (Y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>39%</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>55%</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>35%</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>48%</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>5</td>
<td>1</td>
<td>78%</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>50%</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>31%</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>66%</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>78%</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>67%</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>69%</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>57%</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>75%</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>63%</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>54%</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>82%</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>78%</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>73%</td>
</tr>
</tbody>
</table>

**Objective 1: Identify the importance of different constraints with respect to workflow reliability.**
The results of entropy and mutual information calculation are shown in Table 3.5. In Table 3.5, \( H(X) \) in column (2) represents the uncertainty in the constraint discussions or the amount of information generated by constraints. Constraint \( X_4 \) (“material availability”) and \( X_7 \) (“design and working method clarification”) both have the highest entropy at 2.26 bits. \( X_4 \) was brought up in 14 meetings. When it was discussed, the number of “material availability” related issues ranged from one to four, with a great level of uncertainty. The typical issues were coordination for on-time material delivery and material quality. For example, four times \( X_4 \) constraint was addressed in week two. The first one was material quality problem: the precast concrete pile supplier did not cast anchor bolt sleeves in cap or secure them in the voids. The second one was that 14 in. diameter pipes were not available when needed for girder erection. The GC’s project engineer needed to call the supplier and make sure they were going to be delivered by the next day at 2 PM. The third \( X_4 \) constraint was that the delivery of 45 in girders at span XX was pushed from Friday to Saturday due to delay in pipe spreader delivery. If the pipe supplier kept delaying, the girders would have to be further postponed to the next Tuesday or Wednesday. The fourth \( X_4 \) constraint was that the two rebar suppliers did not have on-time delivery which caused pile drivers to be idle and frustrated. The two suppliers should have had communicated more frequently, and the GC needed to monitor delivery status. The “Design and working method clarification” constraint was brought up in 15 meetings with a frequency ranging from one to four. Typical issues were methods to handle cracks in casing and water infiltrating, differences in survey and actual installation locations and elevations, and developing a working method for pile installation.

Constraint \( X_6 \) (“space availability”) has the lowest entropy at 0.31 bits. This means there was little uncertainty associated with the “space availability” as a constraint. It was either
not brought up as an issue often or it was brought up as a routine without much surprise. In the case of this project, X6 was only brought up once in 18 weeks. Because the project was constructed in a widely open space and considerable buffer was maintained among pile, cap, girder, and deck installations, X6 was not considered as a constraint in most meetings. Issues with space coordination were often resolved in daily huddle meetings. The only time it was brought up was in week 15 to clear out parking under span XX in two weeks.

Table 3.5. Entropy and mutual information for PPC in two categories

<table>
<thead>
<tr>
<th>Constraints</th>
<th>H(X)</th>
<th>H(X) Rank</th>
<th>H(Y)</th>
<th>H(X,Y)</th>
<th>I(X,Y)</th>
<th>I(X,Y) Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>0.50</td>
<td>7</td>
<td>0.99</td>
<td>1.35</td>
<td>0.14</td>
<td>5</td>
</tr>
<tr>
<td>X2</td>
<td>1.49</td>
<td>6</td>
<td>0.99</td>
<td>2.22</td>
<td>0.27</td>
<td>1</td>
</tr>
<tr>
<td>X3</td>
<td>1.91</td>
<td>4</td>
<td>0.99</td>
<td>2.78</td>
<td>0.12</td>
<td>6</td>
</tr>
<tr>
<td>X4</td>
<td>2.26</td>
<td>1</td>
<td>0.99</td>
<td>3.13</td>
<td>0.12</td>
<td>6</td>
</tr>
<tr>
<td>X5</td>
<td>2.22</td>
<td>3</td>
<td>0.99</td>
<td>3.04</td>
<td>0.17</td>
<td>3</td>
</tr>
<tr>
<td>X6</td>
<td>0.31</td>
<td>8</td>
<td>0.99</td>
<td>1.23</td>
<td>0.07</td>
<td>8</td>
</tr>
<tr>
<td>X7</td>
<td>2.26</td>
<td>1</td>
<td>0.99</td>
<td>3.02</td>
<td>0.23</td>
<td>2</td>
</tr>
<tr>
<td>X8</td>
<td>1.88</td>
<td>5</td>
<td>0.99</td>
<td>2.71</td>
<td>0.16</td>
<td>4</td>
</tr>
</tbody>
</table>

H(Y) is the entropy in PPC when it is classified into two groups. H(Y) can be interpreted as the amount of uncertainty in PPC or the amount of information needed to eliminate the uncertainty in PPC. Uncertainty in PPC arises from the unpredictability of next week’s PPC, that is, whether it is going to fall in group A or B. As Table 3.5 shows, the amount of information needed to eliminate the uncertainty in PPC is equal to 0.99 bits. Since the maximum possible value for entropy is 1.0 bits for a variable with two possible outcomes, a PPC with an entropy of 0.99 bits is highly uncertain.

I(Xi,Y) is the mutual information, or the amount of information that is shared between each constraint and PPC. Higher mutual information means that discussing that constraint in meetings is more effective in impacting PPC. For example, in the column (5) of Table 3.5, the
constraint $X_2$ (“equipment availability”) has the highest value of mutual information at 0.27 bits. “Equipment availability” was important in this project because this project was an equipment-intensive type of project. The typical issues are hammer grab break down which needed repairing, renting and buying a new replacement, checking crane capacity, and problems with speciality equipment such as pressure washer, piling template damage, etc. Although the entropy of $X_2$ was 1.49 bits (i.e. it ranked number 6 among all constraint entropies), its mutual information $I(X_2,Y)$ was the highest. This means that managers routinely expected “equipment availability” issues brought up in meetings and there was less uncertainty with this constraint. However, $X_2$ constraint discussion had a strong impact on PPC. On the contrary, $X_4$ (“material availability”) constraints were brought up often at meetings with different frequencies (which means more surprise) but it did not have much impact on improving PPC. Constraint $X_6$ (“space availability”) had both low entropy and mutual information values, which means that $X_6$ was not much of uncertainty in discussion and it did not have much impact on PPC either.

Figure 3.3 shows the entropy and mutual information values of the eight constraints. The red lines are the average of entropies (1.6 bits) and mutual information (0.16 bits). If a constraint has low entropy, it implies that the constraint was discussed in meetings with a stable level of occurrence, at either a routinely low or high frequency. In this project, constraint $X_6$ (“space availability”) and $X_1$ (“external conditions”) had low entropies. They were both rarely mentioned in meetings. As mentioned before, there was not much space related problem for this project. Also, workers were used to and prepared for working in the marine environment and coastal weather. They both have low impact on PPC. $X_2$ (“equipment availability”) had higher entropy, which means that compared with $X_6$ and $X_1$, $X_2$ was discussed more. Most of
the time when it was discussed, there was one issue. There were only two meetings that had
“equipment availability” discussions more than once. Almost every time, there was a problem
with either hammer grab, pile cutter, or crane capacity. Because the project heavily depends
on equipment, discussion on X2 constraint had a strong impact on PPC. This was reflected by
the highest mutual information value of X2. Constraint X3, X4, X5, X7, and X8 had higher
entropy, while X5, X7, and X8 has stronger impact on PPC.

![Figure 3.3. Entropy and mutual information for constraints](image)

**Objective 2:** Quantify each constraint removal's impact on improving workflow
reliability.

Once the importance of each constraint was determined, expected improvement in PPC
can be calculated using the following steps. First, determine the relative importance of
constraint removal discussions by dividing the mutual information of each constraint with PPC
by the total mutual information of all constraints. For example, the relative importance of EC
X1 is \( \frac{i(X_1,Y)}{\sum_i i(X_i,Y)} = \frac{0.14}{1.28} = 11\% \). Next, multiply the relative importance of each constraint by the
overall PPC improvement, which is the difference between the average PPC of group A and B
in Table 3.2. For instance, PPC improvement by “external conditions” constraints removal discussions is equal to $0.11 \times 27\% \approx 3\%$.

Figure 3.4 shows “equipment availability” discussions ($X_2$) had the highest (5.6%) contribution to PPC improvement, followed by a 4.9% improvement from “design and working method clarification” ($X_7$) discussions. This was because these constraints had direct and immediate impact on PPC. $X_2$ and $X_7$ were mainly discussed to resolve equipment unavailability issues and decide on alternative plan (i.e. rent second hammer grab) or to clarify procedures for resolving an existing problem (i.e. cut the pile that has reached the design capacity above the minimum tip elevation) that had paused the project.

**Figure 3.4.** Expected PPC improvement by constraints removal discussions in meetings

*Objective 3: Determine the optimal order of addressing constraints at weekly planning meetings*

An easy solution to determine the order of discussing constraint is to start discussions under the constraint with the highest impact ($X_2$) and then gradually move to the discussion items under next lower impact ($X_7$, $X_5$, $X_8$, .... $X_6$) constraints. However, organizing meeting discussions in this way neglects the information sharing between each pair of constraints. For
example, when participants discussed items that fell into “labor availability” and “material availability” constraints, they also addressed “prerequisite work readiness” constraint.

This study used a Chow-Liu tree to identify the order of addressing constraints at weekly meetings. Chow-Liu tree shows an optimized order to obtain the required information for PPC improvement. There were two main steps for creating the tree in Figure 3.5. The first step was to calculate mutual information among each pair of variables $I(X_i, X_j)$. In the second step, a maximum-weight spanning tree was created. The first node of the tree was selected as Y variable or PPC. The second node, $X_2$, was selected because it had the highest mutual information (0.27 bits as shown in Table 3.5) with PPC. $X_7$ was selected next because it had the highest mutual information with $X_2$. Given $X_2$, the remaining entropy (or conditional entropy) in PPC was 0.42 ($H(Y) = 5/18*(-3/5*log_2(3/5) – 2/5*log_2(2/5)) + 3/18*(-1/3*log_2(1/3) – 2/3*log_2(2/3)) = 0.42$). This shows entropy in PPC has been reduced from 0.72 bits to 0.42 bits and 0.30 bits of information were gained by knowing the $X_7$ (“design and working method clarification”) constraint. This process was repeated until all notes were added to the tree, while skipping adding edges that would create a loop.

As shown in Figure 3.5, discussing the constraints according to the sequence of $X_2$, $X_7$, $X_8$, $X_4$, and $X_1$ in the tree, project managers can reduce a total of 0.99 bits of uncertainty in PPC. Constraints $X_5$, $X_6$, and $X_3$ do not result in information gain for decreasing PPC. This is because information in those categories was already represented by other constraints listed above them in the Chow-Liu tree. Figure 3.5 shows that “equipment availability” had a higher priority for PPC improvement compared to “material availability” and “labor availability”. The reason can be that labor and material, in many cases, can be shared among different activities while this was not possible for equipment. For instance, a concrete journeyman can work one
day for a footing crew and another day for a deck crew, but the major equipment used for these tasks was completely different (A Bidwell paving machine was used to place concrete on the deck while footings were placed using a crane and bucket).

**Objective 4:** Measure information gain from constraint removal discussion to reduce uncertainty in workflow reliability.

![Chow-Liu tree for constraints removal discussion](image)

**Figure 3.5.** Chow-Liu tree for constraints removal discussion

Figure 3.6(a) and (b) illustrates the reduction of total uncertainty in PPC (0.99 bits) by addressing constraints during weekly meetings. In Figure 3.6(a), constraints are addressed
based on the order determined using the Chow-Liu tree greedy algorithm. The difference between Figure 3.6(a) and (b) is the order in which constraints are addressed.

![Graph](image)

**Figure 3.6.** Uncertainty reduction in PPC based on constraints removal discussions ordering

Figure 3.6(a) implies that the information required for removing uncertainty can be gained by addressing constraints in the order of X₂, X₇, X₈, X₄, and X₁. In Figure 3.6(b), however, constraints are being addressed based on their mutual information with PPC (Table 3.5), starting from highest mutual information to lowest, until required information is gained for removing uncertainty. In the latter case, X₂, X₇, X₅, X₈, X₁, X₃, and X₄ constraints should be addressed in order to gain the same amount of information for improving PPC. The latter case needs to address more constraints in order to gain the same amount of information for PPC improvement. The reason for this observation is that a greedy algorithm based on Chow-Liu tree incorporates information sharing between constraints. This method sorts constraints based on the shared amount of information and guaranteeing the other part of information, which is not shared, is useful for improving PPC. In the case of sorting based on the highest mutual information however, adding a new constraint may provide a higher amount of unique information; but there is no guarantee that the new information is useful for PPC improvement.
3.6 Conclusions

This study contributes to the project management body of knowledge by demonstrating the application of analytical tools to assist project managers in planning and conducting planning meetings more effectively. It described an application of an information theory-based analysis to evaluate the relative importance of constraint discussion at the weekly planning meetings for a significant self-performed and horizontal construction project, along with the order in which constraints should be discussed. Information theory approach was used to develop a framework for measuring the amount of uncertainty and information sharing in construction meetings. A Chow-Liu tree was developed to guide project managers on the optimum sequence to discuss constraints so that the constraints will be addressed in the order of their impact and information sharing simultaneously. As a result, redundancy in the remaining constraint discussions will be reduced. The step-by-step analysis is repeatable so that the same framework can be utilized for other construction projects and planning meetings to improve constraints removal efficiency.

Since the project examined is linear and repetitive, statistical analysis was conducted to identify possible autocorrelations in the data. IBM SPSS Statistics v.25 was used to measure and plot the average correlation between PPC values in a time series and previous values of the series measured for lag lengths of 1 to 8. No statistically significant correlations were found with an alpha of 0.15.

Results show that “equipment availability”, “design and working method clarification”, and “prerequisite work readiness” were the three most important constraints for increasing workflow reliability. Analysis indicates that removal of these three constraints could help PPC improvement by almost 14%. The reason for this finding was that bridge project construction
is categorized among equipment-intensive projects. For example, the hammer grab was among the most important tools in pile installation and it determined the drilling progress. “Design and working method clarification” constraint also was essentially important and had direct impact on PPC where certain activities in the project were passed because of unexpected problems. For example, there were instances where piles were cracked, and instructions were provided on how to repair the cracks.

The basic premise of this approach was that when constraints share more information and are discussed subsequently, less interruption and self-repeating occurs. For example, Figure 3.6 suggested discussing “prerequisite readiness” constraint after equipment and materials availability constraints. This is because in this project many items in “prerequisite readiness” were also addressed during discussing “equipment availability” and “materials availability” constraints or are related to these constraints.

It should be emphasized that the project studied in this paper is almost completely self- performed and therefore somewhat unusual. However, the developed methodology is applicable for subcontracted projects. It should be noted that some discussions (such as deciding on working methods) could impact the workflow reliability in the long run, and their impact is not measurable by the PPC of an immediately following week. Therefore, it is possible that results in this paper have underemphasized the value of some constraints removal discussions. Future research can extend the time frame for PPC to address this limitation. This research measured the occurrence of constraint discussion and did not weigh the severity of the discussions because the project engineer on this project determined that the severities were similar. Future research can consider severity aspect when calculating entropies by recording
and classifying duration of constraint discussions, or by classifying length of discussions (i.e. word counts) in meeting minutes.
CHAPTER 4. COMPARATIVE STUDY ON THE PERCEPTION OF CAUSES FOR CONSTRUCTION TASK DELAY IN CHINA AND THE U.S.

4.1 Abstract

Rapidly growing construction markets in China and the U.S. have provided opportunities for contractors to venture into foreign industries. In order to help project managers to understand fundamental differences in culture and the way projects are managed, it is useful to identify and compare root causes of delay and construction management practices in China and the U.S. The objectives of this research are to 1) identify the most prevalent causes of task delay, 2) discover the underlying factor structure associated with starting time and duration delays in China, and 3) develop recommendations to assist construction companies effectively address the potential causes of delay in China and the U.S.

In this study, two questionnaire surveys for government projects performed by civilian contractors were administered to contractors in China and the U.S. Based on the 150 usable responses from China and 124 usable responses from the U.S., the similarities and differences perceived by crew members, middle managers, and high-level managers in both countries were examined. This study also quantitatively examined the underlying structure of the causes of delay using factor analysis and developed strategies to help contractors better understand cultural differences and working environments. The findings may help construction project managers and field managers to better understand the root causes of the differences in order to develop effective strategies to reduce delay and improve project productivity performance of international projects.
4.2 Introduction

According to the China Global Investment Tracker, the value of Chinese overseas investment and construction projects was $279.8 billion in 2017, of which $24.9 billion was invested in the U.S. (China Global Investment Tracker, 2019). At the same time, more design and construction and project management companies were venturing into China’s giant construction market (Ling and Li 2016). For example, in 2012, Bechtel, the U.S. international contractor, signed an agreement to provide project management consulting services to the China Nuclear Power Engineering Company (CNPE), a subsidiary of the China National Nuclear Corporation (Bechtel 2012). In 2017, AECOM, the U.S. international contractor, won a 2 billion dollar contract for constructing a new kids-show theme park in China that is anticipated to open between 2020 and 2021 (Global Construction Review 2017). In 2009, China Construction America, a subsidiary of the China State Construction Engineering Corporation, China’s largest construction conglomerate, started renovating the Alexander Hamilton Bridge in New York City. Completed in July 2014, this project was the largest completed contract ($420M) in the history of the New York State Department of Transportation (NYSDOT) (M & J Engineering P.C 2015).

Projects performed by the international contractors often involve a large amount of investment, high visibility, and additional risks in a foreign market. Monitoring and controlling the project schedule, and avoiding delay are management priorities (Shang and Pheng 2014; Arditi et al. 2017). Previous studies have shown that causes of delay, their magnitude, and possible solutions are different in different countries (Arditi et al. 2017; Wambeke et al. 2011; Al-Kharashi and Skitmore, 2009; Sambasivan and Soon, 2007). Therefore, it is critical to
identify and compare root causes of delay and construction management practices in China and the U.S. to help project managers to adopt to the new market and culture effectively.

The objectives of the research are to: 1) identify the most prevalent causes of task starting time and duration delay for construction projects in China and compare them with the ones of the U.S., 2) discover the underlying factor structure responsible for covariation in the individual causes of task starting time and duration variation in China, and 3) develop recommendations to assist construction companies to effectively address the potential causes of delay. The findings will benefit international contractors considering entering the foreign market or working in the foreign countries as it can help them to better understand the difference in delay causes, develop strategies to mitigate risks, and have a smoother transition to the new environment.

This research divides construction task delay into two parts: task starting time delay and task duration delay. Task starting time delay is a period of time by which a task starting time is postponed from the plan. Task duration delay is a period of time by which task duration is extended from the plan. A construction task delay can be caused by starting time delay, duration delay, or both. The research team conducted two questionnaire surveys to government projects performed by civilian contractors, one in China and another in the U.S., to investigate the problem. The survey in China was distributed to sixteen construction projects in ShanDong Province and collected 214 responses in summer 2018. The survey in the U.S. was distributed to 260 companies throughout the U.S. and collected 124 usable responses. Details can be found in Wambeke et al. (2011). The research analyzed survey results in five steps. First, the research identified and compared the top causes of task starting time delay and duration delay in China and the U.S. Second, Explanatory Factor Analysis (FEA) was performed to identify the
underlying factor structure responsible for covariation in the individual causes in China. Finally, a decision support system was developed to assist construction companies to effectively address the potential causes of delay.

4.3 Literature Review

4.3.1 Causes of Task Starting Time and Duration Delay

Assaf and Al-Hejji (2006) defined construction project delay as “the time overrun either beyond completion date specified in a contract, or beyond the date that the parties agreed upon for delivery of a project.” Ndekugri et al. (2008) defined contract delay as “any occurrence that affects a contractor’s progress or makes him/her work less efficiently than would otherwise have been the case.” Lindhard (2014) defined construction task delay as “negative variation” which occurs when a work task is completed after the deadline. Wambeke et al. (2011) used variation to measure task delay and divided variation into task starting time variation and task duration variation. They defined task starting time variation as the difference between planned starting time and actual starting time. Duration delay is the difference between planned task duration and actual duration. Burr (2016) also proposed to divide task delay into starting and duration delay. He referred to task delay as the “shift in timing of the start, or finish of a discrete critical/non-critical activity” or “an increase in the duration of a discrete critical/non-critical activity, or series of critical/non-critical activities.” This research divided task delay into starting time delay and duration delay because a task delay can be caused by a delayed start, extended duration, or both. Dissecting delay in the two parts helps reveal the root causes.

Construction schedules are prone to a high level of delay due to the dynamic environment. Delay can result from: 1) external causes outside the project environment, such
as extreme weather conditions (El-Adaway 2012) and nonstationary market demand (Ahmad 1999; Barriga et al. 2005), and 2) internal causes related to the project such as workforce motivation (Han et al. 2008; Arashpour et al. 2012), and quality issues causing rework (Josephson et al. 2002; Love and Smith 2003). Wambeke et al. (2011) administered a nationwide survey in the U.S. to identify the most prevalent causes of task starting time and duration delay. By conducting an extensive literature review they identified 50 causes of delay and classified them further under eight precondition categories. They found that the top 10 causes of task starting time and duration delay in the U.S. were: 1) turnaround time from engineers when there is a question with a drawing, 2) completion of previous work, 3) obtaining required permits, 4) the quality of documents (errors in design and/or drawings), 5) rework, 6) socializing, 7) people arriving late and/or leaving early, 8) weather impacts, 9) lack of crew skills/ experience, and 10) needing guidance/instruction from supervisor. Additionally, Wambeke et al. (2011) used factor analysis to identify nine underlying factors that accounted for approximately 75% of the variance in the data by conducting factor analysis. These nine factors were: 1) senior management coordination, 2) material management, 3) prerequisites and constructability, 4) crew management, 5) tools and Personal Protective Equipment, 6) supervisor skills and communication, 7) standards and complexity, 8) labor force management, and 9) equipment coordination.

4.3.2 Comparison between China and the U.S. Construction Productivity

Shen et al. (2011) used published activity-based construction labor productivity data to perform a labor productivity comparison for China and the U.S. They found Chinese construction labor productivity lags behind its U.S. counterparts. However, this lag was more pronounced in equipment-intensive construction activities. Smaller gaps in construction labor
productivity were observed between the two countries for labor-intensive activities (Shen et al. 2011). There is evidence that Chinese labor productivity can overtake the U.S. productivity when there is no significant equipment is involved. Chui and Bai (2010) measured Chinese labor productivity by collecting on-site productivity data in Chongqing, China. In comparison with the U.S. productivity from R.S. Means (2009), they found Chinese labor productivity in building a masonry wall is surprisingly higher than the U.S. labor productivity. Their analysis showed that it would take 26.28 hours for a Chinese crew and 119.48 labor-hours for a U.S. crew to complete a total of 100 m² partition walls.

In general, previous research found that construction industry in China is less developed in its legal framework, industrial structure, technological level, and international market share compared to the construction industries in the U.S., Japan, and the U.K. (Xu et al. 2005). The average number of employees of Chinese construction enterprises was 31 times more than that of the U.S. in 2000, while the output per person of Chinese construction enterprises in terms of dollars was approximately 23 times less than that of their U.S. counterparts that year (Xu et al. 2005). Chinese construction industry is noted as heavily labor-intensive compared to the U.S. (Zhao et al. 2009).

Studies indicate that there is a significant difference between the Chinese construction labor productivity and its U.S. counterpart, where productivity was measured as output (in terms of the U.S.$) per employee. Xu et al. (2005) stated that the labor productivity of the Chinese construction industry was about 4.3% of its U.S. counterpart. Wu et al. (2007) reached a similar conclusion adjusting the exchange rate between China and the U.S. using purchasing power parity. Other studies also indicated lower labor productivity in the Chinese construction industry compared to its counterparts in other developed countries (Shen et al. 2006; Zhao et
al. 2009; Liu et al. 2016). The authors found limited research in this area that was published more recently.

4.3.3 Construction Labor in China

Construction is a labor-intensive industry in China (Shen et al. 2006). A large percentage of construction labor comes from rural areas and is highly unskilled with little education (Zeng 2003; Liu and Jin 2007). According to Zeng (2003), from 38 million laborers working in the Chinese construction industry in 2002, 27 million were rural laborers. Most of these laborers form a temporary workforce, receiving low salary and no welfare (Sha and Jiang 2003).

The lack of well-trained human resources is considered as one of the most serious weaknesses contributing to the poor business performance of many Chinese contractors (Zhao et al. 2009). In 2016, rural migrant workers in the Chinese construction industry were 19.7% of the total, making it the second largest industry in China that creates jobs for this group (Song et al. 2018; National Bureau of Statistics of the People’s Republic of China, 2017). This is because the low salary and poor working conditions contribute to the unattractiveness of the construction industry to well-trained people (Zhao et al. 2009).

During the 2000’s population growth slowed in China and fewer young workers entered into construction industry (China Labour Bulletin 2015). Therefore, the average age of construction labor in China started to climb. According to the China Labour report (2015), at the current stage, the average age of construction labor in China is between 40 to 50 and it is hard to find laborers younger than 30 working on the construction sites. This trend is expected to continue in China because of two reasons (China Labour Bulletin 2015): 1) construction jobs have become less attractive to younger generation because they are unsafe, insecure, and
poorly paid; and 2) older laborers are forced to stay on the job because they do not have a pension or any other kind of social security benefits to support them in their old age.

Despite the shortage of skilled construction labor in China, it seemed that construction laborers have not had much bargaining power in past decades. According to Zhao and Du (2002) Chinese construction laborers are largely employed by domestic contractors and they can be hired or dismissed easily in response to the work fluctuations faced by the contractors. Chih et al. (2016) found that construction laborers in China perceive job insecurity (i.e. contract breach) negatively affects their performance and contributes to a loss in labor productivity.

Previous scholars also have addressed issues related to “overburden” in China. Shang and Pheng (2014) mentioned laborers at construction jobsites in China have to work for longer hours, even on weekends and holidays, to keep a project on track. According to them, laborers are often treated as machines, rather than companies’ assets. Labor overburden in China could be related to the clients’ unreasonable deadlines, considering labor productivity benchmarks and high competition between contractors to win a project. Overburden also will introduce additional risks to the Chinese construction project because as laborers get older their ability to work long hours diminishes and the likelihood of serious injury increases (China Labour Bulletin 2015).

4.4 Method

4.4.1 Questionnaire Surveys

In order to compare and contrast the causes for task delay in China and the U.S., two similar questionnaire surveys were developed by the same research group. One survey was conducted in China and the another in the U.S. Each survey includes three sections. The first section asked respondents to refer to the most recent project he or she had completed. It asked
for project background information including project location, size and type, the type of organization to which respondents belong (that is, Owner, General Contractor (GC), Subcontractor, or Designer), the number of employees in the organization, the company size, and the company revenue. It also asked respondents for background information, such as position, years of experience in construction, and education. The second part listed eight categories and asked respondents to evaluate the impact of each category on starting time and duration delay. The eight categories are listed in Table 4.1. The third section contains specific individual causes of delay in task starting time and duration grouped in eight categories. The survey in the U.S. contained 50 causes. The details of the causes can be found in Wambeke et al. (2011).

Due to the difference in culture, arrangements for labor hiring and payment, working habits, and use of terminologies, the research team conducted three in-depth interviews and five pilot surveys to collect feedback and revise the survey questions for causes in China. The goal was to maintain the maximum level of similarity between the two sets of survey questions while adjusting the questions to suit construction projects in China. The first two interviews were conducted with a Senior Chief Engineer and a Project Chief Engineer separately. They had on average over 25 years of working experience in construction and over seven years of experience in their current position. The third interview was conducted with a senior labor agent/dealer. He had over 30 years of experience in labor agency and is one of the main labor agents in the city. The individuals interviewed gave three types of suggestions. First, to add questions omitted, or China specific questions. For example, they suggested to add “Summer harvest, autumn harvest”. Most Chinese construction workers are from the countryside. They are part time farmers and part time construction workers. In the seasons when farm work is not
busy, they migrate to cities and work on construction projects. During harvest seasons, typically from late May to early June for summer harvest and late September to early October for autumn harvest, workers take about two weeks leave to return hometown to harvest. This is a common practice for construction workers in many parts of China. The second type of suggestions were to use specific or special terms commonly used in Chinese construction industry to refer to some of the causes. For example, instead of “Work complexity” and “Low degree of repetition” under the “Detailed design and work method” category, the experts suggested using “Construction task complexity’ and “Complex structure and no standard floor”. The third type of suggestions was to delete or combine some causes. “Lack of experience on similar tasks” and “Worker/crew lack of skills/experience to perform the tasks(s) being asked of them” were combined to “Inexperienced workers.” “Socializing” and “Absenteeism” were deleted because workers are hired on a daily basis and paid by the amount of work completed daily.

After completing these revisions, the questionnaire was given to two groups of project managers to further confirm that the questions are understandable, accurate, and adequate. The pilot studies totally surveyed 24 managers at various management levels, from Senior Chief Engineer to foremen. The results of 44 causes in total for China are listed in the column (1) of Table 4.1. The 50 causes for the U.S. are listed in the column (2).
<table>
<thead>
<tr>
<th>Category</th>
<th>Cause of Delay (China)</th>
<th>Cause of Delay (U.S.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>1. Prerequisite readiness</td>
<td>Obtaining required permits to start the work</td>
<td>Obtaining required permits to start the work</td>
</tr>
<tr>
<td></td>
<td>Completion of previous work</td>
<td>Completion of previous work</td>
</tr>
<tr>
<td></td>
<td>Quality check and prerequisites’ approval</td>
<td>Rework being required**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poor quality of previous work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inspections for completed work**</td>
</tr>
<tr>
<td>2. Detailed design</td>
<td>Constructability issues in design</td>
<td>Design constructability</td>
</tr>
<tr>
<td></td>
<td>Design changes</td>
<td>Errors in design or drawings)</td>
</tr>
<tr>
<td></td>
<td>Insufficient drawings before starting construction*</td>
<td>Turnaround time from engineers</td>
</tr>
<tr>
<td></td>
<td>Long owner’s response time*</td>
<td>Strict requirements**</td>
</tr>
<tr>
<td></td>
<td>Long consultant’s response time</td>
<td>Quality control requirements**</td>
</tr>
<tr>
<td></td>
<td>Vague and unclear drawings details*</td>
<td>Work complexity</td>
</tr>
<tr>
<td></td>
<td>Non-standard and complex structure</td>
<td>Work sequence or method is not well planned**</td>
</tr>
<tr>
<td></td>
<td>Nonspecific construction method instructions</td>
<td>Low degree of repetition**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inadequate instruction on detailed working method</td>
</tr>
<tr>
<td>3. Labor force</td>
<td>Summer and autumn harvest*</td>
<td>Socializing (talking with fellow workers)**</td>
</tr>
<tr>
<td></td>
<td>Laborers were called out to other projects</td>
<td>Absenteeism**</td>
</tr>
<tr>
<td></td>
<td>Not enough laborers</td>
<td>People arriving late and/or leaving early**</td>
</tr>
<tr>
<td></td>
<td>Unstable labor force</td>
<td>Low morale and/or lack of motivation**</td>
</tr>
<tr>
<td></td>
<td>Inexperienced labor (newbie)</td>
<td>Getting moved to another job/task</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crew size is inadequate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Personnel turnover (i.e., new employees)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Experience on similar tasks (i.e. learning curve)**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Worker/crew lack of skills/experience</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Language barrier**</td>
</tr>
<tr>
<td>4. Tools and equip.</td>
<td>Elevator unavailability*</td>
<td>Personnel lift (no operator, not the priority, maintenance)</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------------</td>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Small equipment misplaced/maintenance*</td>
<td>Power tools (used by someone else, maintenance)**</td>
</tr>
<tr>
<td></td>
<td>Tower crane unavailability</td>
<td>Crane or forklift (unavailable, no operator, maintenance)</td>
</tr>
<tr>
<td></td>
<td>Hand operated tools misplaced/maintenance</td>
<td>Hand tools (used by someone else, misplaced, maintenance)</td>
</tr>
<tr>
<td></td>
<td>Vertical transportation machinery not available</td>
<td>Other heavy equipment (i.e. loader) not available</td>
</tr>
<tr>
<td></td>
<td>Horizontal transportation machinery not available</td>
<td>Personal protective equipment not available**</td>
</tr>
<tr>
<td>5. Material and components</td>
<td>Material moved twice</td>
<td>Material needs to be moved to where you need it</td>
</tr>
<tr>
<td></td>
<td>Late material delivery</td>
<td>Material to arrive from distributor or supplier</td>
</tr>
<tr>
<td></td>
<td>Supplied material mismatch</td>
<td>Trying to get consumables**</td>
</tr>
<tr>
<td></td>
<td>Incorrect material size</td>
<td>Error in material size</td>
</tr>
<tr>
<td></td>
<td>Other heavy equipment (i.e. loader) not available</td>
<td>Error in material type</td>
</tr>
<tr>
<td>6. Job site cond.</td>
<td>Overcrowded work area/job site congestion</td>
<td>Overcrowded work area/job site congestion</td>
</tr>
<tr>
<td></td>
<td>Hard reaching work surface</td>
<td>Difficult access to work area</td>
</tr>
<tr>
<td></td>
<td>Inconvenient layout/Restricted field</td>
<td>Site layout—distance from material storage</td>
</tr>
<tr>
<td></td>
<td>Poor traffic monitoring and control*</td>
<td></td>
</tr>
<tr>
<td>7. Information flow</td>
<td>Wait to get answers to questions you have about the design or drawing</td>
<td>Wait to get answers to questions you have about the design or drawing</td>
</tr>
<tr>
<td></td>
<td>Geological survey does not match actual conditions*</td>
<td>Need guidance or instruction from supervisor</td>
</tr>
<tr>
<td></td>
<td>Not getting guidance from the supervisor</td>
<td>Lack of field manager (foreman) skill/knowledge</td>
</tr>
<tr>
<td></td>
<td>Insufficient management staff</td>
<td>Coordination between different trades</td>
</tr>
<tr>
<td></td>
<td>Coordination issues among activities</td>
<td>Overcommitment because of a tight work schedule</td>
</tr>
<tr>
<td></td>
<td>Overcommitment</td>
<td>Foreman availability</td>
</tr>
<tr>
<td></td>
<td>Team leader lacks management skills</td>
<td>Change in scope of work</td>
</tr>
<tr>
<td>8. Weather/obj.</td>
<td>Plan adjustment (Change in scope of work)</td>
<td>Team leader lacks communication skills</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------------------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Communication between: owner/engineer and project manager</td>
<td>Communication between: project manager and foreman**</td>
</tr>
</tbody>
</table>

* Only for China  
** Only for the U.S.

The questionnaires were distributed to 16 projects in Shandong Province from June 2018 to August 2018. In order to ensure the quality of survey, the researchers first briefly introduced the purpose and basic concepts and ensured the confidentiality of the responders’ and projects’ identities. The research team was available for the entire duration of the survey to answer any questions for clarification. A total of 214 responses were collected.

### 4.5 Analysis and Results

#### 4.5.1 Survey Responses

This study used a two-step approach to screen the data and identify the usable responses. The first step was to remove any response that had less than 25% of the questions answered. The second step used a three-times-interquartile range (3 × IQR) as a cutoff point to remove outliers (Iglewicz and Hoaglin 1993). A total of 50 useable responses were identified from the survey in China and 124 useable responses from the survey in the U.S.
The managers for projects in China were divided into three groups according to their level of responsibilities. They are Senior Chief Engineers (high level managers, 11%), Project Managers and Project Chief Engineers (middle level managers, 30%), and site managers including installation engineers, safety officers, foremen (site level managers, 59%). 97.3% of respondents worked for a General Contractor (GC) company while the rest worked for the owner (government and private), subcontractors, consultant and engineering firms, or labor union companies. On average, respondents had seven years of experience working in construction industry with a minimum of one year and maximum of 41 years; 82.4% of them had 1 to 10 years of experience. In terms of education level, 88% of the respondents had a university degree (associate degree or bachelor’s degree), 6.7% had master’s degree, and the remaining 5.3% had a high school diploma or below. Nearly 80% of the respondents worked in companies that had $14 M - $1.4 B revenue per year and 41.3% had $700 M - $1.4 B revenue per year. 71.3% of the respondents were working on projects’ size between $14M and $140M.

The demographic of the survey in the U.S. can be found in Wambeke et al. (2011).

4.5.2 Research Objective 1: To identify the most prevalent causes of task start time and duration delay for construction projects in China and compare them with those in the U.S.

In order to determine the most prevalent causes of task start time and duration delay in China, the 44 causes were rank-ordered in three classifications, crew/labor, middle, and high management levels, based upon the amount of delay caused in hours per week. Figure 4.1 lists the top five causes of task starting time delay at three management levels. Figure 4.2 shows the top five causes of task duration delay. The causes perceived for projects in China are highlighted in blue and the ones for projects in the U.S. are highlighted in red. The length of
the bar represents the average number of hours delayed per week. The numbers beside the bars are the ranks for the causes.

Figure 4.1. Top 5 causes of starting time delay for projects in China and the U.S.
Fig. 4.1(a) shows that at the crew/labor level, Chinese managers perceive that the top five causes for starting time delay are Summer and Autumn Harvest, Limited Space Availability, Obtaining Required Permits, Insufficient Drawings before Starting Construction, and Design Changes. The top five causes for the U.S. are Completion of Previous Work, Turnaround Time from Engineers, Wait to Get Answers to Questions, Need Guidance or Instruction from Supervisor, and People Arriving Late and/or Leaving Early. Similarly, the top five causes perceived by middle and high-level management for projects in China and the U.S. are listed in Figure 4.1(b) and Figure 4.1(c).
Comparing the causes for three levels of management, the research team found that the number of common causes between China and the U.S. increases with higher level of management. Higher level managers perceive more delay in task starting time. For example, executive managers in China and the U.S. perceived in average 1.84 h/week and 2.08 h/week variation in task start time respectively, whereas, labor/crew in China and the U.S. perceived in average 1.05 h/week and 0.95 h/week variation respectively.

Figure 4.1 shows that Obtaining Required Permits is ranked consistently high (as the top three) for all levels in China. Project managers revealed that one of the permit related problems is that restrictions are issued when there are events with high international visibility. For example, a project can be requested to stop between 7 to 20 days when government leaders meet high profile foreign leaders, a city hosts large international sport games, or local government holds international summits. Construction restrictions can be implemented to reduce air pollution or dust, lighten the traffic burden from detours and material delivery trucks, and to ensure safety. Contractors often received notification about one to two months in advance and restrictions are strictly enforced. In order to resume projects, contractors need to obtain the required permits again. Given tight project schedule, managers at all levels feel this is a significant cause for starting time delay. The same cause is also ranked as the top two for duration delay by crew and middle level management.

Summer and Autumn Harvest and Design Changes are both ranked high for crew and middle level. The reason why Summer and Autumn Harvest is a significant cause is explained in the Questionnaire Surveys section. As to Design Changes, due to rapidly growing economic and market demand, owners often require a project to be completed on a tight schedule. Public owners need infrastructure projects such as airports, high-speed rail stations, and highways to
accelerate construction to start service soon and enhance government reputation. Private owners need residential and commercial projects completed quickly to obtain a return on investment and stabilize cashflow. Therefore, drawings are often completed on a tight schedule, which leads to more design changes in the construction phase.

An interesting observation in Figure 4.1 is that “Turnaround Time from Engineers” and “Wait to Get Answers to Design Questions You Have about Design or Drawings” are ranked high from the U.S. side, as the top two and three, by respondents in all the levels. The finding here is consistent with previous research. Kimpland (2009) found that “slow responses to questions” was one of the top two external factors that impacted productivity. It should be noted that these two causes are essentially the same; the question pertaining to turnaround time was included in two areas of the survey. But those causes are not as highly ranked in China. There are two reasons. First, in China design companies provide comprehensive design service, including architecture, structural engineering, mechanical engineering, water supply & sewerage engineering, and electrical engineering. Therefore, questions can be addressed directly with a single contact point. Second, there are a large number of private design companies and high competition among them. In order to maintain good relationships with clients and obtain future jobs, design companies are highly motivated to provide quick response to questions. Questions usually are answered right way or within two to three days. It is common for architects and engineers in a design company to work overtime. One senior engineer said that he often sees designers work seven days, including three overnights, per week when the design needs to be completed for a tight deadline.

Figure 4.2 shows that in China, the higher the level of management, the less duration delay is experienced. This is opposite to the U.S. and is counterintuitive. The reason is that
when there is potential delay, high-level management can request overtime and add workers, which is a feasible and common practice in China. The pressure is shifted to mid- or crew level management. It is common for construction craft workers to work overtime on extended hours and days. In our survey, 7% of survey respondents worked five days per week, 65% worked 6 or 6.5 days per week, and 28% worked seven days per week. 29% of respondents worked eight hours per day, 39% worked nine to ten hours per day, 21% worked eleven to twelve hours per day, and 11% worked above 12 hours per day.

In China, most construction craft workers are farmers from villages and migrate to cities to work on construction sites to earn extra income. Usually a village has a tradition of passing down a specialized skill, such as carpentry or masonry craft, to the next generations. They form groups to work in cities together and are led by a senior, experienced village leader. Those village leaders report to labor dealers whom they trust. A labor dealer has a long-term partnership with multiple village leaders and can direct from hundreds to thousands of workers through them. When a general contractor wins a project, they can choose to self-perform or subcontract-out. If it is self-performed, a general contractor hires a labor dealer and the labor dealer directs craft workers to projects. If it is subcontracted, subcontractors hire a labor dealer.

Large construction companies can have in-house labor dealers. Once receiving payment from contractors, labor dealers pay village leaders and village leaders pay workers. Based on extensive experience, labor dealers and village leaders know very well about the minimum number of workers to complete a task in a required duration. Workers are paid daily based on the quantity completed. Workers stay on construction site for the entire duration of their jobs except taking leave for two weeks for each harvest season. Workers are away from family for months and live on construction sites. General contractors provide simple
boardrooms. A large construction site can have as many as 5,000 workers who live and work on site. This explains why workers work on extended hours and days regularly. They are motivated to utilize the time away from family to earn more income. This also explains why Socializing and People Arriving Late and/or Leaving Early are ranked very low for China. If there is a need to accelerate construction, dealers can dispatch hundreds of workers from his contact in hours. Therefore, the pressure of acceleration is usually not felt as strongly for high-level managers.

Three out of five top causes perceived by the high-level managers in China are related to labor and staff availability. Labor availability is also regarded as the top cause from the crew level. This reflects the trend in skilled labor shortages.

4.5.3 Research objective 2: To discover the underlying factor structure responsible for task starting time and duration delay in China.

Construction tasks are often interconnected and the delay of one task can affect other tasks. Therefore, it is necessary to consider multicollinearity among the causes of delay. Multicollinearity refers to the high degree of correlation (linear dependency) among two or more independent variables, which also means lack of orthogonality among them (Alin, 2010).

Factor analysis is a statistical approach to grouping variables in a dataset based on strong correlations among them (Fabrigar and Wegener 2012). The Kaiser-Meyer-Olkin (KMO) method was used in the factor analysis to measure sampling adequacy and determine whether or not the collected data was sufficiently large to perform factor analysis. Kaiser (1974) recommends a KMO value greater than 0.60. The KMOs of the correlation matrix for starting time and duration delay were 0.785 and 0.882, which are above the minimum required KMO.
A correlation matrix was developed to show the correlation between each pair of delay causes. The principal axis factoring method was then used to identify factors, that is, groups of causes that are highly correlated to each other. Next, a varimax rotation method was used to rotate the factors to preserve orthogonality, meaning that the resultant factors are uncorrelated. This also maximizes loading onto each factor, resulting in more interpretable factors (Field 2005). The result of the rotation step is called a rotated factor matrix (or factor pattern matrix) where elements of the matrix are simply bivariate correlations between each delay cause and its associated factor. The final step is to interpret the rotated solutions which involves identifying the variables with high loadings (loadings greater than 0.4 are recommended) on given factors. It is common to assign a brief name to each factor based on shared conceptual meaning of these variables. More details of factor analysis process can be found in Wambeke et al. (2011) and O’Rourke and Hatcher (2013). IBM SPSS Statistics v.25 was used to perform the factor analysis for this research.

Table 4.2 and Table 4.3 show the rotated factor matrix for task starting time delay and task duration delay respectively. Six factors were identified which account for 64% of the overall variance of the starting time delay. A description of the 6 factors is provided below.

*Factor 1: Leadership and management coordination.* The individual causes that loaded this factor were leadership insufficient communication, overcommitment, leadership management ability, supervisor guide, coordination between works, insufficient management stuff, poor communication within the construction unit, and plan adjust. With the exception of “plan adjust”, all of these causes are generally associated with the ability of management to coordinate and communicate efficiently.
Factor 2: Design and specification clarification. Most of the variables in this factor address the availability and clarity of design, specifications and working methods. Clarity of design details and working method is essential because when details are not clear, workers will likely have to wait for information coming from an owner or consultants.

Factor 3: Hand tools and transportation. This factor contained several causes of delay pertaining to availability and serviceability of hand tools, small equipment, and horizontal and vertical transportation which are important for reducing start time variation.

Factor 4: Labor and material availability. The name for this factor is self-explanatory. Except for “Wait to Get Answer for Design Questions” and weather, the other five variables in this factor address unavailability of workers/staff and materials when they are required in specific locations at a jobsite.

Factor 5. Space availability and site layout. All the four items in this factor, including hard reach surface, traffic condition, limited space, and inconvenient layout, deal directly with space availability and accessibility on construction sites.

Factor 6. Material quality. Incorrect material size, material mismatch, and incorrect material quality are the top three causes that loaded this factor. When material quality is low, there will likely be a greater quality control requirement and the work sequence can be affected.

Five factors were identified to account for 72% of the overall task duration delay, as shown in Table 4.3. Since in general, the factors are very similar to the ones identified for the starting time delay in Table 2, only the first factor is discussed in detail.

Factor 1. Communication. Except overcommitment and plan adjust, all the other eight variables in this factor directly or indirectly are related to communication. For example, insufficient management stuff can cause poor communication between units or stakeholders.
### Table 4.2. Task start time delay rotated factor matrix

<table>
<thead>
<tr>
<th>Variables</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cronbach's Alpha</td>
<td>0.881</td>
<td>0.909</td>
<td>0.919</td>
<td>0.878</td>
<td>0.869</td>
<td>0.822</td>
</tr>
<tr>
<td>Leader Insuffi. Commu.</td>
<td>0.853</td>
<td>0.192</td>
<td>0.15</td>
<td>0.207</td>
<td>0.117</td>
<td>0.269</td>
</tr>
<tr>
<td>Overcommitment</td>
<td>0.767</td>
<td>0.228</td>
<td>0.24</td>
<td>0.099</td>
<td>0.32</td>
<td>0.053</td>
</tr>
<tr>
<td>Leader Mgmt. Ability</td>
<td>0.759</td>
<td>0.117</td>
<td>0.07</td>
<td>0.224</td>
<td>0.08</td>
<td>0.319</td>
</tr>
<tr>
<td>Supervisor Guide</td>
<td>0.619</td>
<td>0.037</td>
<td>0.442</td>
<td>0.111</td>
<td>0.135</td>
<td>0.124</td>
</tr>
<tr>
<td>Coordinate Bet. Works</td>
<td>0.615</td>
<td>0.231</td>
<td>0.207</td>
<td>0.243</td>
<td>0.365</td>
<td>0.262</td>
</tr>
<tr>
<td>Insuffi. Mgmt. Stuff</td>
<td>0.584</td>
<td>0.133</td>
<td>0.192</td>
<td>-0.041</td>
<td>0.322</td>
<td>0.054</td>
</tr>
<tr>
<td>Poor Commu. Unit</td>
<td>0.488</td>
<td>0.214</td>
<td>0.25</td>
<td>0.214</td>
<td>0.203</td>
<td>0.076</td>
</tr>
<tr>
<td>Plan Adjust</td>
<td>0.426</td>
<td>0.179</td>
<td>0.165</td>
<td>0.35</td>
<td>0.124</td>
<td>0.26</td>
</tr>
<tr>
<td>Consult. Response Late</td>
<td>0.205</td>
<td>0.823</td>
<td>0.348</td>
<td>0.045</td>
<td>0.005</td>
<td>0.057</td>
</tr>
<tr>
<td>Details Not Clear</td>
<td>0.184</td>
<td>0.806</td>
<td>0.311</td>
<td>0.257</td>
<td>0.061</td>
<td>-0.04</td>
</tr>
<tr>
<td>Owner Response Late</td>
<td>0.228</td>
<td>0.796</td>
<td>0.109</td>
<td>0.295</td>
<td>0.012</td>
<td>0.188</td>
</tr>
<tr>
<td>Insufficient Drawing</td>
<td>0.128</td>
<td>0.654</td>
<td>0.116</td>
<td>0.229</td>
<td>-0.059</td>
<td>0.205</td>
</tr>
<tr>
<td>Construction Method</td>
<td>0.146</td>
<td>0.622</td>
<td>0.21</td>
<td>0.091</td>
<td>0.264</td>
<td>0.047</td>
</tr>
<tr>
<td>Prerequisite Readiness</td>
<td>-0.019</td>
<td>0.557</td>
<td>0.084</td>
<td>0.182</td>
<td>0.279</td>
<td>0.086</td>
</tr>
<tr>
<td>Quality Check</td>
<td>0.098</td>
<td>0.471</td>
<td>0.096</td>
<td>0.086</td>
<td>0.231</td>
<td>0.122</td>
</tr>
<tr>
<td>Hand Tools</td>
<td>0.248</td>
<td>0.288</td>
<td>0.819</td>
<td>-0.039</td>
<td>0.109</td>
<td>0.182</td>
</tr>
<tr>
<td>Small Equipment</td>
<td>0.215</td>
<td>0.252</td>
<td>0.778</td>
<td>0.275</td>
<td>0.121</td>
<td>0.16</td>
</tr>
<tr>
<td>Horizontal Transportation</td>
<td>0.227</td>
<td>0.314</td>
<td>0.762</td>
<td>0.098</td>
<td>0.175</td>
<td>0.142</td>
</tr>
<tr>
<td>Vertical Transportation</td>
<td>0.17</td>
<td>0.191</td>
<td>0.612</td>
<td>0.054</td>
<td>0.006</td>
<td>0.223</td>
</tr>
<tr>
<td>No People</td>
<td>-0.084</td>
<td>0.116</td>
<td>0.164</td>
<td>0.765</td>
<td>0.125</td>
<td>-0.012</td>
</tr>
<tr>
<td>Wait to Get Answer</td>
<td>0.283</td>
<td>0.219</td>
<td>0.042</td>
<td>0.676</td>
<td>0.026</td>
<td>-0.067</td>
</tr>
<tr>
<td>Weather</td>
<td>0.149</td>
<td>0.159</td>
<td>-0.130</td>
<td>0.588</td>
<td>0.195</td>
<td>0.313</td>
</tr>
<tr>
<td>Material Not Ontime</td>
<td>0.207</td>
<td>0.356</td>
<td>0.039</td>
<td>0.551</td>
<td>0.169</td>
<td>0.139</td>
</tr>
<tr>
<td>Unstable Staff</td>
<td>0.106</td>
<td>0.145</td>
<td>0.148</td>
<td>0.542</td>
<td>0.245</td>
<td>0.337</td>
</tr>
<tr>
<td>Material Moved Twice</td>
<td>0.289</td>
<td>0.39</td>
<td>0.113</td>
<td>0.523</td>
<td>0.393</td>
<td>0.05</td>
</tr>
<tr>
<td>Workers Called</td>
<td>0.273</td>
<td>0.197</td>
<td>0.358</td>
<td>0.506</td>
<td>0.062</td>
<td>0.282</td>
</tr>
<tr>
<td>Hard Reach Surface</td>
<td>0.445</td>
<td>0.164</td>
<td>0.099</td>
<td>0.036</td>
<td>0.695</td>
<td>0.284</td>
</tr>
<tr>
<td>Traffic Condition</td>
<td>0.232</td>
<td>0.146</td>
<td>0.235</td>
<td>0.076</td>
<td>0.668</td>
<td>0.136</td>
</tr>
<tr>
<td>Limited Space</td>
<td>0.182</td>
<td>0.068</td>
<td>0.022</td>
<td>0.318</td>
<td>0.637</td>
<td>0.015</td>
</tr>
<tr>
<td>Inconvenient Layout</td>
<td>0.193</td>
<td>0.181</td>
<td>0.041</td>
<td>0.385</td>
<td>0.577</td>
<td>0.156</td>
</tr>
<tr>
<td>Incorrect Mater. Size</td>
<td>0.22</td>
<td>0.148</td>
<td>0.329</td>
<td>0.095</td>
<td>0.168</td>
<td>0.756</td>
</tr>
<tr>
<td>Material Miss Match</td>
<td>0.357</td>
<td>0.173</td>
<td>0.289</td>
<td>0.157</td>
<td>0.055</td>
<td>0.672</td>
</tr>
<tr>
<td>Incorrect Mater. Quality</td>
<td>0.18</td>
<td>0.152</td>
<td>0.404</td>
<td>0.084</td>
<td>0.175</td>
<td>0.595</td>
</tr>
<tr>
<td>Objective Reasons</td>
<td>0.269</td>
<td>0.11</td>
<td>0</td>
<td>0.306</td>
<td>0.365</td>
<td>0.465</td>
</tr>
</tbody>
</table>
Table 4.3. Task duration delay rotated factor matrix

<table>
<thead>
<tr>
<th>Variables</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Communication</td>
<td>Hand Tool /Transport</td>
<td>Design/Specs</td>
<td>Material Avail/Qual</td>
<td>Layout/Space</td>
</tr>
<tr>
<td>Cronbach's Alpha</td>
<td>0.968</td>
<td>0.935</td>
<td>0.924</td>
<td>0.900</td>
<td>0.900</td>
</tr>
<tr>
<td>Poor Commu. Unit</td>
<td>0.903</td>
<td>0.141</td>
<td>0.141</td>
<td>0.147</td>
<td>0.105</td>
</tr>
<tr>
<td>Coordination Bt. Works</td>
<td>0.884</td>
<td>0.124</td>
<td>0.186</td>
<td>0.202</td>
<td>0.103</td>
</tr>
<tr>
<td>Leader Insuffi. Commu.</td>
<td>0.845</td>
<td>0.193</td>
<td>0.227</td>
<td>0.108</td>
<td>0.173</td>
</tr>
<tr>
<td>Own-Des-Con Commu.</td>
<td>0.842</td>
<td>0.177</td>
<td>0.225</td>
<td>0.139</td>
<td>0.136</td>
</tr>
<tr>
<td>Overcommit</td>
<td>0.820</td>
<td>0.128</td>
<td>0.185</td>
<td>0.14</td>
<td>0.205</td>
</tr>
<tr>
<td>Plan Adjust</td>
<td>0.777</td>
<td>0.093</td>
<td>0.15</td>
<td>0.204</td>
<td>0.016</td>
</tr>
<tr>
<td>Leader Mgmt. Ability</td>
<td>0.734</td>
<td>0.235</td>
<td>0.191</td>
<td>0.059</td>
<td>0.167</td>
</tr>
<tr>
<td>Insuffi. Mgmt. Stuff</td>
<td>0.703</td>
<td>0.28</td>
<td>0.173</td>
<td>0.026</td>
<td>0.304</td>
</tr>
<tr>
<td>Supervise Guide</td>
<td>0.685</td>
<td>0.308</td>
<td>0.188</td>
<td>0.032</td>
<td>0.318</td>
</tr>
<tr>
<td>Wait to Get Answer</td>
<td>0.655</td>
<td>0.124</td>
<td>0.222</td>
<td>0.216</td>
<td>0.267</td>
</tr>
<tr>
<td>Small Equipment</td>
<td>0.234</td>
<td>0.875</td>
<td>0.156</td>
<td>0.18</td>
<td>0.037</td>
</tr>
<tr>
<td>Hand Tools</td>
<td>0.161</td>
<td>0.871</td>
<td>0.182</td>
<td>0.114</td>
<td>-0.049</td>
</tr>
<tr>
<td>Horizontal Transport</td>
<td>0.236</td>
<td>0.729</td>
<td>0.196</td>
<td>0.144</td>
<td>0.294</td>
</tr>
<tr>
<td>Elevator</td>
<td>0.122</td>
<td>0.683</td>
<td>0.117</td>
<td>0.369</td>
<td>0.088</td>
</tr>
<tr>
<td>Vertical Transport</td>
<td>0.411</td>
<td>0.616</td>
<td>0.14</td>
<td>0.169</td>
<td>0.194</td>
</tr>
<tr>
<td>Workers Called</td>
<td>0.319</td>
<td>0.554</td>
<td>0.314</td>
<td>0.366</td>
<td>-0.031</td>
</tr>
<tr>
<td>Material Moved Twice</td>
<td>0.245</td>
<td>0.529</td>
<td>0.212</td>
<td>0.315</td>
<td>0.469</td>
</tr>
<tr>
<td>Owner Response</td>
<td>0.388</td>
<td>0.132</td>
<td>0.770</td>
<td>0.021</td>
<td>0.242</td>
</tr>
<tr>
<td>Unstable Staff</td>
<td>0.126</td>
<td>0.119</td>
<td>0.756</td>
<td>0.465</td>
<td>-0.027</td>
</tr>
<tr>
<td>Details Not Clear</td>
<td>0.352</td>
<td>0.277</td>
<td>0.738</td>
<td>-0.061</td>
<td>0.182</td>
</tr>
<tr>
<td>Consulting Response</td>
<td>0.424</td>
<td>0.205</td>
<td>0.735</td>
<td>0.013</td>
<td>0.228</td>
</tr>
<tr>
<td>Construction Method</td>
<td>0.297</td>
<td>0.209</td>
<td>0.673</td>
<td>0.005</td>
<td>0.171</td>
</tr>
<tr>
<td>No People</td>
<td>0.091</td>
<td>0.012</td>
<td>0.662</td>
<td>0.430</td>
<td>0.001</td>
</tr>
<tr>
<td>Insufficient Drawings</td>
<td>0.086</td>
<td>0.455</td>
<td>0.53</td>
<td>0.309</td>
<td>0.075</td>
</tr>
<tr>
<td>Complex Structure</td>
<td>0.11</td>
<td>0.359</td>
<td>0.529</td>
<td>0.415</td>
<td>0.114</td>
</tr>
<tr>
<td>Harvest</td>
<td>0.228</td>
<td>0.259</td>
<td>0.121</td>
<td>0.683</td>
<td>0.173</td>
</tr>
<tr>
<td>Material Not Ontime</td>
<td>0.395</td>
<td>0.231</td>
<td>0.183</td>
<td>0.658</td>
<td>0.226</td>
</tr>
<tr>
<td>Quality Check</td>
<td>0.089</td>
<td>0.397</td>
<td>0.126</td>
<td>0.579</td>
<td>0.401</td>
</tr>
<tr>
<td>Prerequisite Work</td>
<td>0.076</td>
<td>0.321</td>
<td>0.101</td>
<td>0.532</td>
<td>0.250</td>
</tr>
<tr>
<td>Incorrect Mater. Size</td>
<td>0.486</td>
<td>0.38</td>
<td>0.184</td>
<td>0.52</td>
<td>0.083</td>
</tr>
<tr>
<td>Inconvenient Layout</td>
<td>0.399</td>
<td>0.128</td>
<td>0.227</td>
<td>0.139</td>
<td>0.782</td>
</tr>
<tr>
<td>Limited Space</td>
<td>0.209</td>
<td>0.035</td>
<td>0.103</td>
<td>0.202</td>
<td>0.707</td>
</tr>
<tr>
<td>Hard Reach Surface</td>
<td>0.421</td>
<td>0.112</td>
<td>0.168</td>
<td>0.262</td>
<td>0.644</td>
</tr>
</tbody>
</table>
4.5.4 Research objective 3: To develop recommendations to assist construction companies to effectively address the potential causes of delay.

The ultimate goal of this research is to help construction companies in directing their efforts for eliminating causes of delay. Although the ideal situation is to eliminate all the causes of delay, that may not be practical. Thus it will be important to prioritize the causes of delay to be targeted for reduction as it enables managers to get the “biggest bang for the buck”.

This research considered three aspects of the causes for delay to prioritize the causes for elimination. They are: 1) the impact of the causes on the overall delay, 2) the relationship (correlation) among the causes, and 3) the differences in delay factor structure.

Figure 4.3 and Figure 4.4 demonstrate the percentage of delay explained by each factor for the starting time and duration delay in the U.S. and China respectively. These percentages show the relative contribution of the identified factors to the overall task start time and duration delay. Comparing Figure 4.3(a) and Figure 4.4(a), the total starting time delay is more evenly distributed among the identified factors in China. In the U.S., however, the “senior management coordination” factor contributed to the task starting time delay significantly more than the other five factors. A similar trend is found when comparing task duration delay factors in Figure 4.3(b) and Figure 4.4(b). Figure 4.3(b) shows that only one task duration delay factor (prerequisites and constructability) accounts for 45% of the overall variation (29% out of 64%), with the other four factors together accounting for the remaining 55% variation. The finding implies that causes of delay are more centralized in the U.S. compare to China.

Figure 4.3 and Figure 4.4 provide a basis to compare the impact of the factors on the overall delay while considering the first two aspects, impact and multicollinearity. In order to consider the third aspect, the research also measured the differences in factor ranking and
examined how it interacts with impact. This study took the average rank of causes in each factor to determine the rank of factors for starting time and duration delay. Then the factor ranks between China and the U.S. were compared to determine the level of difference between factors, which is shown as the Y-axis in Figure 4.5. The X-axis of Figure 4.5 is the impact on total delay, which is the percentage of the overall delay explained by each factor. The red lines are average values for impact and difference at 12% and 16.7% respectively.

Figure 4.3. Delay explained by each factor in the U.S.

Figure 4.4. Delay explained by each factor in China
Figure 4.5 shows that factors can be clustered into three groups. The first group includes “Communication, Leadership, and Management” and “Design and Specifications”. The two factors are perceived similarly in delay ranking for both China and the U.S. They also have a high contributions to overall task delay. Therefore, when project managers move to a project in a different country, they should target those two factors first to minimize delay. The second group has one factor, “Labor and Material Availability”. It has a middle level of similarity and impact. This factor is recommended to be the second priority to address to reduce the causes of delay. The third group included two factors, “Space and Layout” and “Material Quality”, which are perceived the most differently in the two countries and have lower impacts on overall delay.

Separate interviews were conducted with two managers about the results of the survey in China. One was a middle level manager with over 15 years of experience and another one was a senior chief engineer with over 30 years of experience in construction industry. Neither knew the results of the survey. They were asked what their top three causes of delay were. One responded with material availability, design quality, and labor availability. The other named trust in communication, design change, and losing of skilled laborers. The responses of both are consistent with the top factors identified in this research and provides at least some level of validation.
4.6 Conclusions

Delays in construction task starting and duration can have a significant impact on construction productivity and project performance. Monitoring and minimizing delay are especially critical for international projects due to the large amount of investment, high visibility, and potential risks. With the rapid growth in international construction, owners, contractors, and project managers need to understand the similarity and differences in causes of delay to better prepare for operation in the foreign market. It is also critical for them to learn the fundamental differences in culture and the way projects are managed so that they will be able to have more effective communication with partners in foreign countries and take meaningful actions to improve their response to problems.

Although a significant research effort has been devoted to identifying factors affecting construction productivity, previous research has not been conducted in comparing differences in perceived delay by managers in China and the U.S. It is also not clear how the uniqueness in culture and management practice cause the differences and what strategies should be used.
to bridge the difference. This research helped fill this gap of knowledge based on 274 useable survey responses.

This study identified the top ten causes of task starting time and duration delay in China. They are: Permit to Start, Lack of Labor, Design Changes, Harvest, Insufficient drawings, Constructability, Wait to Get Answer to Questions You Have about the Design or Drawing, Weather, Unstable Staff, and Limited Space. Wait to Get Answer to Questions You Have about the Design or Drawing, Design Changes, and Weather were among the top 10 causes of delay in the U.S. (Wambeke et al. 2011). Based on in-depth interviews with local experts, the research examined the differences in culture, the way projects are managed, and how those led to the difference in management priorities. For example, most construction workers in China are also farmers from villages. They live on construction job sites for most months of a year and only return home in summer and fall harvest season and Chinese New Year holidays. Therefore, they are motivated to work on extended hours and flexible to be dispatched to different sites on short notice.

Additionally, factor analysis was performed for the 44 individual causes of delay in China. Six factors were identified that accounted for approximately 71% of the delay. The six factors were: Communication, Leadership and Management; Design and Specs; Hand Tools and Transportation; Labor and Material Availability; Space and Layout; and Material Quality. The research also quantified the contribution of each factor to delay and to the level of difference between China and the U.S. It was interesting to find that the factors that contribute to overall delay the most are also the most similar factors in China and the U.S. They are “Communication, Leadership, and Management” and “Design and Specs”. On the other hand, the factors that contribute least to overall delay are the factors having highest level of
difference. They are “Hand Tools and Transportation”, “Material Quality”, and “Space and Layout”. The most important factors affecting causes of delay are those pertaining to “Communication, Leadership, and Management”, “Design and Specs”, “Labor and Material Availability”, “Hand Tools and Transportation”, “Material Quality”, and “Space and Layout” in descending order. The factors identified during factor analysis, coupled with the top individual causes of delay, may be useful when planning work. The findings will help construction owners, contractors, and construction managers better understand the differences, root causes of differences, and develop effective strategies to reduce task delay and improve project productivity performance.

The major limitation of this research is that the scope and timing of the two surveys are not the same. The survey in China was conducted in ShanDong province in 2018. The survey in the U.S. was conducted nationwide in 2010. However, the findings are still usable and beneficial because of three reasons. First, having over 100 million permanent population, ShanDong is the second largest province in population in China. Its GDP was one trillion Yuan (0.15 trillion US$) in 2017, ranked third highest nationwide. Therefore, the survey result is broadly representative of China. Second, although economic conditions and construction technology have changed since 2010, management practice and culture has not been changed much, especially for government/public projects performed by civilian contractors. This was confirmed by senior project managers in the interviews for validation. They also confirmed that there were no significant changes in the environment for construction industry in general in China over the time period between the two surveys. Third, the survey results were validated by senior project managers in both countries. Therefore, although there
could be some differences due to scope and timing, it was still appropriate and valuable to compare how managers perceive delay causes differently in the surveys.
CHAPTER 5. TO WHAT EXTENT EXPERIENCE OF DELAY SHAPES MANAGERS’ MAKING-DO DECISION: A RANDOM FOREST APPROACH

5.1 Abstract

Making-do, a decision of starting a construction task despite knowing that its preconditions are not fully ready, has been regarded as a type of waste in the construction management literature. Making-do decision is very complex and many factors such as project managers’ perceived degree of precondition readiness, crew utilization, getting a job, owner’s pressure to start a work, etc. may contribute to a making-do decision. However, it remains unclear to what extent project managers’ experience of delay shapes their making-do decision. To fill in the gaps in knowledge this research administered two surveys in China and the U.S. to find to what extent experienced delay due to lack of readiness in task preconditions affects managers’ making-do decision. This research used Mann–Whitney U test to examine whether delaying task starting time when lacking precondition readiness pays off with less duration delay, utilized Random Forest to find important causes of delay which contribute to making-do decision, and employed entropy-based Decision Tree to determine how much uncertainty in making-do decisions can be reduced by knowing managers’ experience of delay in past projects. Results showed that in the U.S. “perfection is the enemy of productivity”, and managers who preferred making-do experienced up to 60% less task duration delay; while the Chinese managers who preferred making-do experienced up to 100% more task duration delay due to lack of readiness in labor, equipment, material, and management/information flow precondition categories. Also, findings revealed that managers’ experience of delay due to unavailability of detailed design and working method instruction is the main contributor to the
U.S. managers’ making-do decision with a contribution as high as 28%. Also, availability of detailed design was the second contributor to Chinese managers’ making-do decision with the contribution level of 17%. The findings of this research will help project managers to better understand underlying factors that trigger making-do decisions in China and the U.S. and have more efficient collaboration and communication when they work on projects located in a foreign country.

5.2 Introduction

Making-do, a decision to start a work despite knowing that preconditions are not fully ready, was referred to as a type of waste in construction projects (Koskela 2004). Making-do is complex and difficult to avoid given the uncertainty of construction site management. It is also both a rational and irrational decision at the same time (Bølviken and Koskela 2016). Although making-do is a locally and momentarily rational strategy to reduce waste, reasoning that “it is better to do something than to do nothing”, in the long run it can be counterproductive from the perspective of the production system and results in waste (Bølviken and Koskela 2016). Therefore, construction managers often have to encounter the dilemma to decide how ready is ready enough to start a task when not all preconditions are met. Answer to this question heavily depends on project managers’ experience on previous making-do decision, which can be different for projects in different countries.

Previous research identified preconditions for tasks execution and emphasized the importance of precondition readiness (Ballard and Howell 1998; Koskela 2000; Jang and Kim 2008; Lindhard and Wandahl 2012; Hamzeh et al. 2015; Wang et al. 2016; Javanmardi et al. 2018), discussed triggers for making-do decision (Koskela 2004; Formoso et al. 2011; Pikas et al. 2012; Koskela et al. 2013), and studied the impact of making-do on project performance
(Formoso et al. 2011; Pikas et al. 2012; Neve and Wandahl 2018). However, it remains unclear
to what extent project managers’ experience of delay in the past shapes their making-do
decision. To fill in the gaps in knowledge, this research administered two surveys in China and
the U.S. to find to what extent experienced delay due to lack of readiness in certain
preconditions affects managers’ making-do decisions. Specifically, the research questions are:
1) whether delaying task starting time when lacking precondition readiness pays off with less
duration delay, 2) which causes of delay are important for making-do decisions, and 3) how
much uncertainty in making-do decisions can be reduced by knowing managers’ experience of
delay in past projects. The research objectives are to: 1) find out whether sacrificing starting
time will pay off with less duration delay, 2) determine the relative importance of delay causes’
contribution to making-do decision, and 3) quantify the amount of uncertainty that can be
reduced in making-do decisions by knowing managers’ delay experience associated with
various causes.

In order to answer the questions, this research administered two surveys to government
projects performed by civilian contractors in China and the U.S. The survey in China was
distributed to sixteen construction projects in ShanDong Province and collected 141 usable
responses in 2018. The survey in the U.S. was distributed to 260 companies throughout the
U.S. and collected 119 usable responses (Wambeke et al. 2011). Based on the survey
responses, the research used Mann-Whitey U test to discover whether there is a significant
difference in experienced duration delay between managers who choose making-do or not.
Using managers' experienced starting time and duration delay as inputs and managers' making-
do preferences as outputs, this study identified important causes of delay and their contribution
to a making-do decision.
5.3 Literature Review

5.3.1 Making-Do

Making-do, as a waste, refers to a situation where a task is started without readiness of all its preconditions, or the execution of a task is continued although the readiness of at least one precondition has ceased (Koskela 2004). Conceptually, making-do is the opposite of buffering. Whereas in buffering there is a positive waiting time for preconditions to get ready before starting a task, in making-do that waiting time is negative (Koskela 2004). Koskela (2004) argued further that besides buffering, “making-do is another penalty due to variability” because it is practiced for maintaining a high utilization rate and/or for avoiding schedule slippage.

Koskela (2000) proposed seven preconditions for smooth execution of construction tasks. These preconditions are: 1) external conditions (i.e. weather), 2) equipment availability, 3) labor availability, 4) material availability, 5) prerequisite work readiness, 6) space availability, and 7) design and working method clarification. Wambeke et al. (2011) added one more precondition category, namely “management/supervision/information flow”, which refers to existence of systems to develop the workplan or schedule, provide guidance or instruction, and to answer questions. Lindhard and Wandahl (2012) recommended two additional preconditions, “safe working condition” and “known working condition”.

Formoso et al. (2011) stated that “making-do has a strong relationship with the concept of improvisation.” This is because when people face a difficult and uncertain situation, they tend to use whatever resources are available to reach their objectives (Cunha 2004). There are numerous factors that influence making-do decisions. For example: perception of the state of readiness, maturity of the work (Pikas et al. 2012), maintaining profitability by utilizing
resources (Koskela 2004; Pikas et al. 2012), start the work just for getting the job (Koskela 2004), and lack of trust and pressure of an immediate response (Formoso et al. 2011; Koskela 2004). When choosing making-do, project managers believe that by starting early, even with lack of preconditions, the task will also be completed earlier (Koskela 2004).

By collecting data from two case studies and performing explanatory data analysis, Formoso et al. (2011) found: (1) the most frequent types of making-do were related to the access and availability of working areas, temporary facilities, protection, and equipment and tools; and (2) the main causes of making-do were the ineffectiveness in providing adequate temporary facilities, poor management of layout/space, and insufficient information. Other researchers have found an apparent correlation between excessive talking and making-do, concluding that excessive talking is a valid making-do indicator (Neve and Wandahl 2018).

Formoso et al. (2011) identified the main impacts of making-do on the performance of construction projects. The main impacts were material waste, poor safety conditions, and reduced motivation. Pikas et al. (2012) collected empirical data over eleven weeks at a large residential construction project. They analysed different scenarios based on task go/no-go decisions and their outcomes (i.e. completed as planned, successful but completed late, and unsuccessful–achieved partial value). Pikas et al. (2012) found that in 57% of cases (12 out of 21 cases) where preconditions were not fully ready, some form of making-do was attempted. Furthermore, they found in half (50%) of the cases of making-do, tasks were stopped before getting completed, therefore, full value was not achieved. Neve and Wandahl (2018) actively participated in weekly Last Planner System (LPS®) meetings and conducted work sampling studies on six trades for three housing refurbishment projects. They found that
making-do is highly likely to be the prevailing reason for the low productivity in refurbishment projects.

Previous research has emphasized the complexity of a making-do decision, suggested stimulating factors behind making-do decisions, and demonstrated the impact of making-do on project performance. However, limited research was found investigating how project managers’ experience on task starting and duration delay shapes their making-do decisions. It is also not clear how the difference in culture and management process of different countries play a role. Therefore, it is valuable to demonstrate to what extent managers’ experiences contribute to their making-do decisions.

5.3.2 Construction Task Delay

Lindhard (2014) defined construction task delay as “negative variation”, which occurs when a work task is completed after deadline. Wambeke et al. (2011) used variation to measure task delay and divided variation into task starting time variation and task duration variation. Burr (2016) also proposed to divide task delay into starting and duration delay. He referred to task delay as the “shift in timing of the start, or finish of a discrete critical/non-critical activity” or “an increase in the duration of a discrete critical/non-critical activity, or series of critical/non-critical activities.” This research divided task delay into starting time delay and duration delay because a task delay can be caused by a delayed start, extended duration, or both. Task starting time delay is the difference between planned starting time and actual starting time. Duration delay is the difference between planned task duration and actual duration. Dissecting delay in the two parts helps reveal the root causes.

Construction schedules are prone to a high level of delay due to the dynamic environment. Delay can result from: 1) external causes outside the project environment, such
as extreme weather conditions (El-Adaway 2012) and nonstationary market demand (Ahmad 1999; Barriga et al. 2005), and 2) internal causes related to the project such as workforce motivation (Han et al. 2008; Arashpour et al. 2012), and quality issues causing rework (Josephson et al. 2002; Love and Smith 2003). Wambeke et al. (2011) administered a nationwide survey in the U.S. to identify the most prevalent causes of task starting time and duration delay. By conducting an extensive literature review they identified 50 causes of delay and classified them further under eight precondition categories. They found that the top 10 causes of task starting time and duration delay in the U.S. were: turnaround time from engineers when there is a question with a drawing, completion of previous work, obtaining required permits, the quality of documents (errors in design and/or drawings), rework, socializing, people arriving late and/or leaving early, weather impacts, lack of crew skills/experience, and needing guidance/instruction from supervisor.

Previous research has studied causes of task delay from various perspectives. But it is not clear how managers’ past experience of delay impacts their estimation of future delay and level of risk tolerance. It will be beneficial to understand the mechanism between experienced delay and assessment of precondition readiness for future tasks.

5.3.3 Random Forest (RF)

Random Forest (RF) introduced by Breiman (2001) is a nonparametric supervised method of machine learning that uses ensemble of multiple classification and regression trees (CART) for classification, prediction, and variable selection (James et al. 2013; Yeh et al. 2014).

RF has several advantages that makes it a suitable machine learning method for variable selection in this study. First, RF can handle large numbers of input variables in a relatively
small sample size with missing values and avoid model over-fitting (Abdel-Rahman et al.
2013; Liu et al. 2018). Second, RF is a nonparametric machine learning method, hence no
assumptions are required to be made about the type of relationship between input and target
variables and the distribution of those variables (Xie et al. 2017). Third, unlike a single decision
tree, RF does not suffer from instability problems and it is more robust with respect to noises
as its algorithm combines and averages results across a large set of decision trees (Breiman
2001; James et al. 2013). Fourth, with specific provisions, RF can handle the multicollinearity
problem among input variables (Strobl et al. 2008; Neville and Tan 2014).

Zhou et al. (2014) developed and employed a RF to predict ground settlements above
tunnels. Their results indicated that the RF method was able to model nonlinear relationships
between vertical and horizontal ground settlements (outputs) and corresponding inputs for the
aspects of tunnel geometry, geological properties, and construction parameters. Xie et al.
(2017) used RF and decision tree to predict the delineation of evacuation zones in the 2050s
and 2090s, based on the predicted sea-level rises and changes of demo-economic features. By
using 10% of data as the validation dataset to evaluate model performance, Xie et al. (2017)
found that the RF outperforms the decision tree in term of the accuracy and Kappa statistic.
Xin et al. (2018) developed three models to evaluate the impact of outdoor ambient
environmental factors on the scaffolding construction productivity. The three models were: (1)
a nonparametric regression model, (2) the generalized additive model (GAM), and (3) a
nonlinear machine learning RF model. They concluded that because RF and GAM models
showed better performance, the relationship between outdoor ambient environment and
construction productivity is nonlinear and should be built by nonlinear models. RF also has
been used for predicting safety accidents caused by excavation of deep foundation pits in
subway stations (Zhou et al. 2018). Researchers found that, in contrast to artificial neural nets (ANN) and Bayesian network (BN), RF can accurately predict safety risks of subway foundation pits based on safety risk level monitoring values, using small and unbalanced data samples. Superiority of RF in prediction and classification has been confirmed by other research studies in construction management. Poh et al. (2018) used five machine learning methods to predict occurrence and severity of accidents on construction project sites based on project-related (project type, percent completed, etc.) and safety inspection-related (crane/lifting operations, falling hazards/openings, etc.) input variables. Those machine learning methods were: decision tree, RF, logistic regression, K-nearest neighbor (KNN), and support vector machines (SVM). During validation, they found RF provides the best prediction performance with an accuracy of 78%.

Based on the literature review of previous application performance of RF, this research adopted the RF approach to analyze project managers’ perceived delay and how it contributes to making-do decision.

5.4 Method

5.4.1 Questionnaire Survey

In order to understand how project managers’ perception in delay contributes to their making-do decision, the research team conducted two surveys, one in China and another in the U.S. Each survey includes three sections. The first section asked project background information including project location, size, type, type of organization respondents belong to, number of employees in the organization, company size, and company revenue. It also asked respondents background information, such as position, years of experience in construction, education, and number of subordinates. The second part asked respondents’ preference of
making-do, whether they prefer to “start” a work or “wait” when the preconditions (labor, material, equipment, etc.) are not fully ready. The third part asked for respondents’ experienced task starting time and duration delay (in terms of hours/week) due to specified individual causes of delay. The survey for the U.S. included 50 causes of delay and was conducted by Wambeke et al. (2011)

The research team maintained the maximum level of similarity between the two sets of survey questionnaires for China and the U.S. while adjusting the questions to suit construction projects in the destination countries. For example, the pilot study group in China suggested to add “Summer harvest, autumn harvest” as a cause of task starting time and duration delay. This was because most Chinese construction workers were from the countryside and during harvest seasons, typically from late May to early June for summer harvest and late September to early October for autumn harvest, workers take about two weeks leave to return hometown to harvest, which subsequently impacts starting time and duration of construction tasks. Totally there were 44 causes of delay identified for the survey in China and 50 for the U.S.

Table 5.1 shows the 44 causes of task starting time and duration delay in China listed in the column (1) and 50 causes for the U.S. task delay in the column (2). The 34 common causes are in black. The 10 special causes in China are highlighted blue and the 17 special causes in the U.S. are in red.

**Table 5.1. Causes for task starting time and duration delay**

<table>
<thead>
<tr>
<th>Category</th>
<th>Cause of Delay (China) (1)</th>
<th>Cause of Delay (U.S.) (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Prerequisite readiness</td>
<td>Obtaining required permits to start the work</td>
<td>Obtaining required permits to start the work</td>
</tr>
<tr>
<td></td>
<td>Completion of previous work</td>
<td>Completion of previous work</td>
</tr>
<tr>
<td></td>
<td>Quality check and prerequisites’ approval</td>
<td>Rework being required**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poor quality of previous work</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Constructability issues in design</td>
<td>Summer and autumn harvest*</td>
<td>Elevator unavailability*</td>
</tr>
<tr>
<td>Design changes</td>
<td>Laborers were called out to other projects</td>
<td>Small equipment misplaced/maintenance*</td>
</tr>
<tr>
<td>Insufficient drawings before starting construction*</td>
<td>Not enough laborers</td>
<td>Tower crane unavailability</td>
</tr>
<tr>
<td>Long owner’s response time*</td>
<td>Unstable labor force</td>
<td>Hand operated tools misplaced/maintenance</td>
</tr>
<tr>
<td>Long consultant’s response time</td>
<td>Inexperienced labor (newbie)</td>
<td></td>
</tr>
<tr>
<td>Vague and unclear drawings details*</td>
<td></td>
<td>Elevator unavailability</td>
</tr>
<tr>
<td>Non-standard and complex structure</td>
<td></td>
<td>Small equipment misplaced/maintenance*</td>
</tr>
<tr>
<td>Nonspecific construction method instructions</td>
<td></td>
<td>Tower crane unavailability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hand operated tools misplaced/maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspections for completed work**</td>
<td>Design constructability</td>
<td>Personnel lift (no operator, not the priority, maintenance)</td>
</tr>
<tr>
<td></td>
<td>Errors in design or drawings)</td>
<td>Power tools (used by someone else, maintenance)**</td>
</tr>
<tr>
<td></td>
<td>Turnaround time from engineers</td>
<td>Crane or forklift (unavailable, no operator, maintenance)</td>
</tr>
<tr>
<td></td>
<td>Strict requirements**</td>
<td>Hand tools (used by someone else, misplaced, maintenance)</td>
</tr>
<tr>
<td></td>
<td>Quality control requirements**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Work complexity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Work sequence or method is not well planned**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low degree of repetition**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inadequate instruction on detailed working method</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Socializing (talking with fellow workers)**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Absenteeism**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>People arriving late and/or leaving early**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low morale and/or lack of motivation**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Getting moved to another job/task</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crew size is inadequate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Personnel turnover (i.e., new employees)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Experience on similar tasks (i.e. learning curve)**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Worker/crew lack of skills/experience</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Language barrier**</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1. (continued)
<table>
<thead>
<tr>
<th>5. Material and components</th>
<th>Vertical transportation machinery not available</th>
<th>Other heavy equipment (i.e. loader) not available</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal transportation machinery not available</td>
<td>Personal protective equipment not available**</td>
</tr>
<tr>
<td>Material moved twice</td>
<td>Material needs to be moved to where you need it</td>
<td></td>
</tr>
<tr>
<td>Late material delivery</td>
<td>Material to arrive from distributor or supplier</td>
<td></td>
</tr>
<tr>
<td>Supplied material mismatch</td>
<td>Trying to get consumables**</td>
<td></td>
</tr>
<tr>
<td>Incorrect material size</td>
<td>Error in material size</td>
<td></td>
</tr>
<tr>
<td>Incorrect material quality*</td>
<td>Error in material type</td>
<td></td>
</tr>
<tr>
<td>Overcrowded work area/job site congestion</td>
<td>Overcrowded work area/job site congestion</td>
<td></td>
</tr>
<tr>
<td>Hard reaching work surface</td>
<td>Difficult access to work area</td>
<td></td>
</tr>
<tr>
<td>Inconvenient layout/Restricted field</td>
<td>Site layout—distance from material storage</td>
<td></td>
</tr>
<tr>
<td>Poor traffic monitoring and control*</td>
<td>Wait to get answers to questions you have about the design or drawing</td>
<td></td>
</tr>
<tr>
<td>6. Job site cond.</td>
<td>Geological survey does not match actual conditions*</td>
<td>Need guidance or instruction from supervisor</td>
</tr>
<tr>
<td></td>
<td>Not getting guidance from the supervisor</td>
<td>Lack of field manager (foreman) skill/knowledge</td>
</tr>
<tr>
<td></td>
<td>Insufficient management staff</td>
<td>Coordination between different trades</td>
</tr>
<tr>
<td></td>
<td>Coordination issues among activities</td>
<td>Overcommitment because of a tight work schedule</td>
</tr>
<tr>
<td></td>
<td>Overcommitment</td>
<td>Foreman availability</td>
</tr>
<tr>
<td></td>
<td>Team leader lacks management skills</td>
<td>Change in scope of work</td>
</tr>
<tr>
<td></td>
<td>Plan adjustment (Change in scope of work)</td>
<td>Foreman communication skills</td>
</tr>
<tr>
<td></td>
<td>Team leader lacks communication skills</td>
<td>Communication between: owner/engineer and project manager</td>
</tr>
<tr>
<td></td>
<td>Poor communication among owner, designer, and –contractor</td>
<td>Communication between: project manager and foreman**</td>
</tr>
<tr>
<td></td>
<td>Poor communication within the construction unit</td>
<td>Communication between: foreman and workers</td>
</tr>
<tr>
<td></td>
<td>Adverse weather (too cold, too hot, rainy, windy)</td>
<td>Weather impacts (excessive heat, cold, wind, rain)</td>
</tr>
<tr>
<td>7. Information flow</td>
<td>Wait to get answers to questions you have about the design or drawing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geological survey does not match actual conditions*</td>
<td>Need guidance or instruction from supervisor</td>
</tr>
<tr>
<td></td>
<td>Not getting guidance from the supervisor</td>
<td>Lack of field manager (foreman) skill/knowledge</td>
</tr>
<tr>
<td></td>
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<td>Overcommitment</td>
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<td></td>
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<td>Communication between: foreman and workers</td>
</tr>
<tr>
<td></td>
<td>Adverse weather (too cold, too hot, rainy, windy)</td>
<td>Weather impacts (excessive heat, cold, wind, rain)</td>
</tr>
</tbody>
</table>
Table 5.1. (continued).

| Objective causes (uncontrollable factors such as –traffic control, noise control, night construction, –and environmental management)* |

The survey in China was distributed to 240 project managers working in public projects in ShanDong province in summer 2018 and received 141 usable responses. The survey in the U.S. was distributed to 260 contractors working in public projects nationwide and received 119 usable responses.

5.4.2 Mann–Whitney U Test

The Mann–Whitney U test is a nonparametric test that compares the central locations of two populations with similar-shape distributions when there are two independent random samples drawn from these populations. This research chose the Mann-Whitney U test because it is more robust than the t-test on non-normal distributions with any potential outliers (Lehamnn 1999). Also, instead of comparing the raw data directly, the Mann–Whitney U test compares the ranked data (Newbold et al., 2012; Norušis 2012). Mann–Whitney U’s null hypothesis is that there is no difference in the central locations of the two populations under consideration, assuming the populations have similar-shape distributions. In our research, the null hypothesis is that there is no difference in the central location of experienced duration delay between the two populations who choose making-do and who do not.

In order to test the null hypothesis, the Mann–Whitney U statistic and Z value are calculated using the following formulas (Newbold et al., 2012):

\[ U = n_1n_2 + \frac{n_1(n_1 + 1)}{2} - R_i \] (5.1)
where U is the Mann–Whitney U, \( n_1 \) is the size of the sample 1 (i.e. managers who choose making-do); \( n_2 \) is the size of the sample 2 (i.e. managers who choose to wait); \( R_1 \) is the sum of the ranks of the sample 1. Observations from the two samples are combined and ranked in ascending order. If there are tied observations, the average of ranks is assigned to all of them.

\[
E(U) = \mu_U = \frac{n_1 n_2}{2}
\]

(5.2)

E(U) is the expected value of U distribution given \( n_1 \) and \( n_2 \). \( \mu_U \) is the mean of the Mann–Whitney U distribution for sample 1 and 2.

\[
Var(U) = \sigma^2_U = \frac{n_1 n_2 (n_1 + n_2 + 1)}{12}
\]

(5.3)

Var(U) and \( \sigma^2_U \) are the variance of U distribution given \( n_1 \) and \( n_2 \).

\[
Z = \frac{U - \mu_U}{\sigma_U}
\]

(5.4)

Equation (5.4) is used to calculate Z value, which will be used to determine whether to reject or accept the null hypothesis according to the chosen significance level of \( \alpha \). In this study, \( \alpha \) is set at 0.05, which is the probability of rejecting null hypothesis when the null hypothesis is true.

5.4.3 Random Forest (RF)

RF approach was used in this study to select the important causes of delay which contribute most to reduce uncertainty in making-do decision. Figure 5.1 shows the RF structure adopted for this research, given an input–output dataset for \( n \) respondents corresponding to making-do. For example, the 141 survey responses from China contain 88 inputs (44 experienced weekly starting time delays and 44 duration delays). The output is 141 choices for making-do. Based on the 141 sets of inputs and outputs, we built matrix \( \{(X_1, Y_1), \ldots, (X_n, Y_n)\}, \ldots, \)
\((X_n, Y_n)\), where \(X_i = \{x_{i1}, x_{i2}, \ldots, x_{ij}, \ldots, x_{im}\}\) is an input vector with \(m=88\) and \(x_j\) is the variable indicating the respondent \(i\)'s experienced starting time or duration delays (h/week); and \(Y_i\) is the output variable which has the two values: 0 for making-do, and 1 for wait. RF algorithm was implemented in the following steps as shown in Figure 5.1 (Breiman 2001; Adusumilli et al. 2013; James et al. 2013):

**Step 1**: Randomly select 60% of the total available responses to grow a tree. For the China survey, 60% of total 141 responses is approximately 85. The remaining 56 responses are called out-of-bag (OOB) sample and will be used later for variable selection.

**Step 2**: Take square root of the number of input variables to determine the number of candidate variables to build a tree. For example, the number of input variables for the China survey is 88. We used \(9 \approx \sqrt{88}\) candidate variables to build a tree.

**Step 3**: Grow the tree using 85 randomly selected observations. In order to grow a tree, the first step is to split a node by finding the best splitting value for each of the 9 randomly selected inputs using Gini Impurity Index, and then select the best input among all inputs to split making-do values. For binary targets, the Gini Index simplifies to \(2\hat{p}_j(1 - \hat{p}_j)\), where \(\hat{p}_j\) is the proportion of the responses that fall into class \(j\) of the node under consideration. Pure node has a Gini Index of zero. The process is repeated until a tree is built to the maximum depth of 5.

**Step 4**: Repeat Step 3 until 100 trees are grown.
This study uses Random Branch Assignments (RBA) (Neville and Tan 2014) method to compute the importance of causes of task delay with respect to their ability in correctly classifying the making-do decision. The main reason for using RBA is that it reflects the true classification power of each input variable by handling multicollinearity and avoiding bias towards correlated input variables (Neville and Tan 2014). The RBA method was implemented through the following steps:

1. Classify OOB responses associated with each tree in RF.
2. Calculate the margin for each node in each tree. Margin in case of a categorical target variable is defined as “the probability of the true class minus the maximum probability among the other classes” (SAS Institute Inc 2017). Margin can be calculated using Equation (5.5) (SAS Institute Inc 2017; Breiman and Cutler 2003):
Margin (ω) = \sum_{j=1}^{J} N_j (\hat{p}_j - \max_{k \neq j} \hat{p}_k) \tag{5.5}

where ω is an internal node of bth decision tree in the forest, J is the number of classes in the categorical target variable (i.e. for the binary making-do target J=2), j is a class of node ω, N_j is the number of responses (observations) that fall into class j of node ω, \hat{p}_j is the proportion of the responses that fall into class j of node ω, k indicates other classes than j in node ω, and \hat{p}_k is the proportion of the responses that fall into class k of node ω. It should be mentioned that “a good model increases the margin” (SAS Institute Inc 2017).

Step 3: Calculate margin increase for each tree. The amount of margin increased by a tree is the difference between the margin of its root node (first node) and sum of the margins of its leaf nodes (end nodes).

Step 4: Randomly assign OOB responses to the child nodes splitted by the variable k. The proportion for random assignment is the same as the proportion of the observations that have fallen into child nodes of the training tree split by the variable k.

Step 5: Repeat steps 1 and 2. Recompute the increase of margin for each tree.

Step 6: Calculate the difference between the original OOB margin increase and the new OOB margin increase for each tree. The new OOB margin increase will be almost certainly less than the original OOB margin increase. This reduction in margin increase is called “margin reduction.”

Step 7: Average margin reduction for the variable k over all trees in RF.

Step 8: Repeat steps 4-7 for every input variable k. The input variables which result in the greatest margin reduction (greatest increase in error) when they are involved in RBA are the most important input variables.
This process will assign a RBA Margin Reduction value to each of the causes of task starting time and duration delay, which represents the relative importance of the causes of task delay for making-do decisions.

5.4.4 Entropy and Information Gain

This research used Information Theory method to analyze the uncertainty reduction in making-do due to the amount of delay in each cause. Entropy was calculated to measure the level of uncertainty. Entropy of a random variable $X$, $H(X)$, is a measure of uncertainty (or impurity) in the variable. Entropy is defined as follows (Shannon 1948):

$$H(X) = \sum_{i=1}^{m} p(x_i) \log_2 \frac{1}{p(x_i)} \text{bits}$$  \hspace{1cm} (5.6)

where $X$ is a discrete random variable with $m$ possible outcomes of $x_i$, $p(x_i)$ is the probability for the random variable $X$ to have the value of $x_i$, $x_i \in \{x_1, x_2, \ldots, x_m\}$. Since entropy uses log base 2, the units are called bits (short for binary digits). The maximum entropy for a random variable $X$ with two possible outcomes (i.e. a binary variable) is 1.00 bit, which occurs when there are equal numbers of observations for each of the two possible outcomes in the data set (or the two possible outcomes have equal chance (50% probability) of happening) (Kelleher 2015). The minimum entropy for a random variable $X$ with two (or more) possible outcomes is 0 bit, which occurs when all the observations in data set have the same value for $X$.

By calculating entropy values for the input variables, we will be able to measure the amount of information gained from each input variable. In the context of this research, information gain measures the amount of information a cause of task delay provides about the making-do decision outcome. To calculate information gain from splitting a node in decision
tree, entropy of the parent node (the node to be split) is compared with the entropy of the child nodes using Equation (5.7) (Alfaro et al. 2019):

\[ \Delta H(\omega, j) = H(\omega) - \sum_{v=1}^{k} \frac{N_v}{N} H(\omega_v) \]  

where \( \omega \) is a parent node in a decision tree, \( j \) is an input variable used for splitting \( \omega \), \( \Delta H(\omega, j) \) is information gained from splitting \( \omega \), \( H(\omega) \) is entropy of the parent node \( \omega \), \( k \) is total number of child nodes (for a binary split, \( k=2 \)), \( N \) is the number or responses (observations) in the node \( \omega \), \( N_v \) is the number or responses in the child node \( \omega_v \), \( \frac{N_v}{N} \) is the proportion of responses in node \( \omega \) in which variable \( j \) takes the value \( v \) and therefore falls into the child node \( \omega_v \), and \( H(\omega_v) \) is entropy of the child node \( \omega_v \). The second part in Equation (5.7) is the expected amount of uncertainty (impurity) after splitting the responses in node \( \omega \) using the input variable \( j \). It is important to note that input variables that result in more information gain are more important for predicting or classifying the target variable. Information gain in this research is measured through the following steps (Kelleher 2015; Sarma 2017). First, we compute entropy of making-do observations form Equation (5.6). The result is the overall uncertainty in making-do which is the first node in the decision tree. Next, for every causes of task starting time and duration we determine the best splitting value to split making do observations into two subsets. Then, we select the best cause of task delay whose best split value yields the highest information gain on making-do. Once the first node, which is making-do observations, is separated into two parts (child nodes), the entropy of making-do observations in child nodes is calculated using Equation (5.6). The total entropy of child nodes gives the remaining uncertainty in making-do. Finally, this research calculates the amount of
information gained from the cause of delay used for splitting the making-do observations by subtracting the total entropy of child nodes from the entropy of the parent node.

Once this process is repeated for every split in the tree, the amount of information gained from every cause of task delay used in the tree is determined. If a cause of delay is used in more than one split in the decision tree, the total information gained by the cause of delay is equal to the sum of information gained from each split. The results demonstrate to what extend managers’ task starting time and duration delay experience contribute to uncertainty reduction in their making-do decisions.

5.5 Analysis and Results

The research team collected 260 survey responses in China and 240 ones in the U.S. A two-step approach was taken to clean the data and identify the usable responses. First, responses with less than 25% of questions answered were removed. Second, the three-times interquartile range (3×IQR) was used as a cut-off point for removing outliers (Iglewicz and Hoaglin 1993). As a result, 141 usable responses and 119 useable ones were identified for the survey in China and the U.S.

Research Objective 1: To test the hypothesis that “managers who choose not to practice making-do experience significantly less duration delay.”

The Mann–Whitney U test was performed to test whether there are significant differences of experienced duration delay between managers who choose making-do and the ones who do not. Results in Table 5.2 shows that there are significantly difference in the amount of duration delay experienced due to nine causes between the making-do and non-making-do groups in China. The making-do group experienced higher duration delay for all nine causes. The causes are “Inexperienced Labor”, “Horizontal Transportation”, “Late
Material Delivery”, “Material Mismatch”, “Incorrect Material Quality”, “Insufficient Management Staff”, “Overcommitment”, “Poor Communication between Owner- Designer-GC”, and “Poor Communication inside Construction Unit.” But in the U.S. results are completely opposite. Managers who preferred making-do experienced significantly less duration delay as a result of 12 causes as listed in Table 5.2. The only exception is “Obtaining Required Permits”.

<table>
<thead>
<tr>
<th>Cause of Delay</th>
<th>Country</th>
<th>Avg. Duration Delay “Making-do” (hr/week)</th>
<th>Avg. Duration Delay “Not Making-do” (hr/week)</th>
<th>( p )-value (Mann-Whitney U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inexperienced labor</td>
<td>China</td>
<td>1.15</td>
<td>0.71</td>
<td>0.026</td>
</tr>
<tr>
<td>Horizontal transportation</td>
<td>China</td>
<td>0.53</td>
<td>0.35</td>
<td>0.040</td>
</tr>
<tr>
<td>Late material delivery</td>
<td>China</td>
<td>0.97</td>
<td>0.57</td>
<td>0.019</td>
</tr>
<tr>
<td>Material mismatch</td>
<td>China</td>
<td>0.50</td>
<td>0.26</td>
<td>0.010</td>
</tr>
<tr>
<td>Incorrect material quality</td>
<td>China</td>
<td>0.65</td>
<td>0.43</td>
<td>0.029</td>
</tr>
<tr>
<td>Insuffi. management staff</td>
<td>China</td>
<td>0.58</td>
<td>0.44</td>
<td>0.029</td>
</tr>
<tr>
<td>Overcommitment</td>
<td>China</td>
<td>0.91</td>
<td>0.60</td>
<td>0.042</td>
</tr>
<tr>
<td>Poor commun. btw. Ow, De, &amp; GC</td>
<td>China</td>
<td>0.88</td>
<td>0.73</td>
<td>0.044</td>
</tr>
<tr>
<td>Poor commun. inside const. unit</td>
<td>China</td>
<td>0.55</td>
<td>0.30</td>
<td>0.042</td>
</tr>
<tr>
<td>Obtaining required permits</td>
<td>U.S.</td>
<td>0.16</td>
<td>0.00</td>
<td>0.023</td>
</tr>
<tr>
<td>Errors in design or drawings</td>
<td>U.S.</td>
<td>0.91</td>
<td>2.27</td>
<td>0.000</td>
</tr>
<tr>
<td>Work complexity</td>
<td>U.S.</td>
<td>0.37</td>
<td>0.96</td>
<td>0.006</td>
</tr>
<tr>
<td>Work sequence</td>
<td>U.S.</td>
<td>0.86</td>
<td>1.81</td>
<td>0.031</td>
</tr>
<tr>
<td>Inadequate instructions</td>
<td>U.S.</td>
<td>0.90</td>
<td>1.73</td>
<td>0.013</td>
</tr>
<tr>
<td>Socializing</td>
<td>U.S.</td>
<td>1.06</td>
<td>1.59</td>
<td>0.047</td>
</tr>
<tr>
<td>Absenteeism</td>
<td>U.S.</td>
<td>0.99</td>
<td>1.70</td>
<td>0.050</td>
</tr>
<tr>
<td>Lack of motivation</td>
<td>U.S.</td>
<td>0.39</td>
<td>0.74</td>
<td>0.042</td>
</tr>
<tr>
<td>Getting moved to another job/task</td>
<td>U.S.</td>
<td>0.89</td>
<td>2.11</td>
<td>0.005</td>
</tr>
<tr>
<td>Experience on similar tasks</td>
<td>U.S.</td>
<td>0.61</td>
<td>1.37</td>
<td>0.003</td>
</tr>
<tr>
<td>Hand tools</td>
<td>U.S.</td>
<td>0.17</td>
<td>0.40</td>
<td>0.011</td>
</tr>
<tr>
<td>Difficult access to work area</td>
<td>U.S.</td>
<td>0.72</td>
<td>1.19</td>
<td>0.024</td>
</tr>
<tr>
<td>Poor commun. btw. owner and PM</td>
<td>U.S.</td>
<td>0.63</td>
<td>1.11</td>
<td>0.038</td>
</tr>
</tbody>
</table>
Results in Table 5.2 also reveal that Chinese managers who choose making-do, experienced up to two times more duration delay compared to the ones who did not choose making-do. However, this result is quite opposite considering the U.S. data. Results indicate that the U.S. managers who choose making-do experienced up to 60% less duration delay compared to managers who did not choose making-do.

**Research Objective 2: to determine the relative importance of delay causes’ contribution to making-do decision**

In order to determine the relative importance of delay causes’ contribution to making-do decision, the research built one matrix for China and one for the U.S. The matrix for China includes 88 input variables (44 for starting time delay and 44 for duration delay) and one binary output variable (making-do, 1 for yes, and 2 for no). The matrix for the U.S. includes 100 input variables and one output variable. The goal is to find which input variables (causes of delay) provide more information about the values of output variable (making-do).

In the first step, RF machine learning method was utilized to select the important input variables with respect to target (making-do) variable. This research used SAS Enterprise Miner (EM) 14.2 to run the RF algorithm. Figure 5.2 shows the relationship between the number of input variables used in tree model and the performance of the tree model, which is measured by misclassification rate. The results show that selecting the first 11 important causes reduces to a 0.21 misclassification rate. Adding 77 more variables will result in an additional reduction of 0.06. Therefore, including the first 11 delay causes gives the tree model “biggest bang for the buck”. For similar reason, 11 causes were selected to build the decision tree model for the U.S.
In order to evaluate the relative importance of the selected causes of task delay, this research (i) calculated RBA margin reduction of the delay causes for both countries (column 3 of Table 5.3 and Table 5.4) and (ii) scaled the RBA values by assigning 100 to the highest RBA margin reduction (column 4 of Table 5.3 and Table 5.4).

In Table 5.3 for China, managers’ top-four experienced delays that influenced their making-do decisions are lack of readiness in 1) materials (“Material mismatch”), 2) design and working method (“Insufficient drawing details”), 3) labor (“Inexperienced workers”), and 4) equipment (“Horizontal transport”). Looking at the U.S. results (Table 5.4), however, we find that causes of task delay that influence managers’ making-do decisions are more confined. Table 5.4 shows that the 4 out of 5 most important causes of delay that contribute to making-do decision belong to readiness of the “design and working method” precondition. Those are experienced amount of task starting time (i.e. XXX_S) and task duration (i.e. XXX_D) variation due to “Design drawing error”, “Lack of instruction working method”, and “Question answer time”.

Figure 5.2. Number of input variables and misclassification rate for decision tree model
Table 5.3. RF variable importance calculation based on RBA Margin Reduction for China

<table>
<thead>
<tr>
<th>Cause of Delay</th>
<th>Number of Splitting Rules</th>
<th>RBA Margin Reduction</th>
<th>Variable Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Mismatch _S</td>
<td>59</td>
<td>0.0428</td>
<td>100</td>
</tr>
<tr>
<td>Insuffi. Drawing Details _S</td>
<td>32</td>
<td>0.0278</td>
<td>65</td>
</tr>
<tr>
<td>Inexperienced Workers _D</td>
<td>30</td>
<td>0.0258</td>
<td>60</td>
</tr>
<tr>
<td>Horizontal Transport _D</td>
<td>16</td>
<td>0.0241</td>
<td>56</td>
</tr>
<tr>
<td>Material Mismatch _D</td>
<td>22</td>
<td>0.0229</td>
<td>54</td>
</tr>
<tr>
<td>Poor Communi. Unit _D</td>
<td>34</td>
<td>0.0222</td>
<td>52</td>
</tr>
<tr>
<td>Incorrect Mater. Quality _D</td>
<td>22</td>
<td>0.0196</td>
<td>46</td>
</tr>
<tr>
<td>Vertical Transport _S</td>
<td>52</td>
<td>0.0195</td>
<td>45</td>
</tr>
<tr>
<td>Incorrect Mater. Quality _S</td>
<td>11</td>
<td>0.0184</td>
<td>43</td>
</tr>
<tr>
<td>Design Change _S</td>
<td>29</td>
<td>0.0181</td>
<td>42</td>
</tr>
<tr>
<td>Inconvenient Layout _S</td>
<td>22</td>
<td>0.0169</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 5.4. RF variable importance calculation based on RBA Margin Reduction for the U.S.

<table>
<thead>
<tr>
<th>Cause of Delay</th>
<th>Number of Splitting Rules</th>
<th>RBA Margin Reduction</th>
<th>Variable Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Draw. Error _D</td>
<td>38</td>
<td>0.0326</td>
<td>100</td>
</tr>
<tr>
<td>Lack Instr. Wk. Method _S</td>
<td>39</td>
<td>0.0206</td>
<td>63</td>
</tr>
<tr>
<td>Access _S</td>
<td>16</td>
<td>0.0202</td>
<td>62</td>
</tr>
<tr>
<td>Ques. Ans. Time _D</td>
<td>39</td>
<td>0.0196</td>
<td>60</td>
</tr>
<tr>
<td>Ques. Ans. Time _S</td>
<td>45</td>
<td>0.0183</td>
<td>56</td>
</tr>
<tr>
<td>Quality Control _D</td>
<td>18</td>
<td>0.0165</td>
<td>51</td>
</tr>
<tr>
<td>Worker Experience _D</td>
<td>36</td>
<td>0.0161</td>
<td>49</td>
</tr>
<tr>
<td>Wait For Answ. _D</td>
<td>31</td>
<td>0.0152</td>
<td>47</td>
</tr>
<tr>
<td>Rework _S</td>
<td>26</td>
<td>0.0148</td>
<td>45</td>
</tr>
<tr>
<td>PPE _S</td>
<td>14</td>
<td>0.0146</td>
<td>45</td>
</tr>
<tr>
<td>Power Tools _S</td>
<td>11</td>
<td>0.0122</td>
<td>37</td>
</tr>
</tbody>
</table>

**Research Objective 3:** *to quantify the amount of uncertainty can be reduced in making-do decisions by knowing managers’ delay experience associated with various causes.*

Once the top 11 input variables are selected, the next step is to identify the information gain obtained from each input variable following the steps discussed in the method section.

For example, Figure 5.3 shows that in China from the total 141 respondents, 62.41% (N=88) decide making-do, while the rest 37.59% (N=53) decide not to. Using Equation (5.6) the entropy of the parent node (Node 1) is equal to \( H_1 = -0.6241 \times \log_2 (0.6241) - 0.3759 \times \log_2 \)
(0.3759) = 0.9551 bits. This number represents uncertainty of making-do in China (Table 5.5, column 4 and row 1). In the same way, entropy values for child nodes, H₂ and H₃, was calculated using Equation (5.6), which resulted in 0.9983 bits and 0.4855 bits of entropy respectively. As discussed in the method section, higher entropy in this paper implies more uncertainty in making-do decisions. This is why Node 2 has the highest entropy, having almost 50% chance of managers deciding making-do, while Node 3 has the lowest entropy (less uncertainty) with almost 90% chance of making-do.

Figure 5.3. First node and its child nodes for decision tree in China

Once the entropy values are calculated for the parent node and the child nodes, this paper uses Equation (5.7) to calculate information gain from splitting the parent node by the cause of delay. In the same example above, information gain from “Material Mismatch_S” is equal to \( H_1 - \left( \frac{103}{141} \times H_2 + \frac{38}{141} \times H_3 \right) = 0.095 \) bits, which is shown in the row 2 and column 2 of Table 5.5.

Table 5.5 (China) and Table 5.6 (U.S.) show the amount of information gained from each of the delay causes when they are used to build the decision tree model for the purpose
of classifying responses with respect to making-do. It should be mentioned that limits were assigned for growing the three models in terms of leaf size and maximum depth. Leaf nodes in a decision tree shouldn’t have less than 5 responses and the tree should not be grown more than 5 generations of child nodes.

The first row of the fourth column in Table 5.5 shows that at the beginning, before doing any classification, there were 0.9551 bits of uncertainty about making-do in China. Every time a cause of delay was used to split making-do into two parts, the amount of uncertainty reduced. The total amount of uncertainty reduction is always equal to total information gain (i.e. for Table 5, $0.9551 - 0.5028 = 0.4523$). For better visualization, results in column 4 of Table 5.5 and Table 5.6 are illustrated in Figure 5.4 (a) and (b) separately. As the figures show, each time a cause of delay is used to split making-do responses, the remaining uncertainty about the making-do decision is reduced.

**Table 5.5.** Uncertainty reduction in making-do by gaining information about experienced amount of delay due to the causes of delay in China

<table>
<thead>
<tr>
<th>Cause of Variation</th>
<th>Information Gain (bits)</th>
<th>Cumulative Info. Gain (bits)</th>
<th>Uncertainty (bits)</th>
<th>% Contribution to Uncertainty Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>---</td>
<td>0.9551</td>
<td></td>
<td>---</td>
</tr>
<tr>
<td>Material Mismatch _S</td>
<td>0.095</td>
<td>0.095</td>
<td>0.8601</td>
<td>21.0%</td>
</tr>
<tr>
<td>Insuffi. Drawing Details _S</td>
<td>0.0868</td>
<td>0.1818</td>
<td>0.7733</td>
<td>19.2%</td>
</tr>
<tr>
<td>Design Change _S</td>
<td>0.0721</td>
<td>0.2539</td>
<td>0.7012</td>
<td>15.9%</td>
</tr>
<tr>
<td>Incorrect Mater. Quality _D</td>
<td>0.0721</td>
<td>0.326</td>
<td>0.6291</td>
<td>15.9%</td>
</tr>
<tr>
<td>Inexperienced Workers _D</td>
<td>0.0423</td>
<td>0.3683</td>
<td>0.5868</td>
<td>9.4%</td>
</tr>
<tr>
<td>Inconvenient Layout _S</td>
<td>0.0345</td>
<td>0.4028</td>
<td>0.5523</td>
<td>7.6%</td>
</tr>
<tr>
<td>Incorrect Mater. Quality _S</td>
<td>0.0252</td>
<td>0.428</td>
<td>0.5271</td>
<td>5.6%</td>
</tr>
<tr>
<td>Poor Communi. Unit _D</td>
<td>0.0243</td>
<td>0.4523</td>
<td>0.5028</td>
<td>5.4%</td>
</tr>
</tbody>
</table>
Table 5.6. Uncertainty reduction in making-do by gaining information about experienced amount of delay due to the causes of delay in the U.S

<table>
<thead>
<tr>
<th>Cause of Delay (1)</th>
<th>Information Gain (bits) (2)</th>
<th>Cumulative Info. Gain (bits) (3)</th>
<th>Uncertainty (bits) (4)</th>
<th>% Contribution to Uncertainty Reduction (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>---</td>
<td>0.7847</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Design Draw. Error_D</td>
<td>0.0995</td>
<td>0.0995</td>
<td>0.6852</td>
<td>23.2%</td>
</tr>
<tr>
<td>Rework_S</td>
<td>0.0821</td>
<td>0.1816</td>
<td>0.6031</td>
<td>19.2%</td>
</tr>
<tr>
<td>Ques. Ans. Time_S</td>
<td>0.0729</td>
<td>0.2545</td>
<td>0.5302</td>
<td>17.0%</td>
</tr>
<tr>
<td>Wait For Answ._D</td>
<td>0.0684</td>
<td>0.3229</td>
<td>0.4618</td>
<td>16.0%</td>
</tr>
<tr>
<td>Lack Instr. Wk. Method_S</td>
<td>0.0447</td>
<td>0.3676</td>
<td>0.4171</td>
<td>10.4%</td>
</tr>
<tr>
<td>Access_S</td>
<td>0.0359</td>
<td>0.4035</td>
<td>0.3812</td>
<td>8.4%</td>
</tr>
<tr>
<td>Worker Experience_D</td>
<td>0.0247</td>
<td>0.4282</td>
<td>0.3565</td>
<td>5.8%</td>
</tr>
</tbody>
</table>

Figure 5.4 (a and b) show that the tree models cannot perfectly classify making-do responses since 0.50 bits (and 0.36 bits) of uncertainty remain about whether managers do making-do or do not, despite knowing the amount of delay they have experienced in the past.

Results in Figure 5.4 (a) and (b) are summarized in Figure 5.5 (a) and (b) to understand the extent precondition categories contribute to making-do decision. The percentage of contribution by each precondition category to the reduction of overall uncertainty in making-do is calculated by summing information gains of causes of delay that fall into one precondition category and dividing it by the original uncertainty in making-do. For example, in Figure 5.5(a), “Material Mismatch_S”, “Incorrect Material Quality_D”, and “Incorrect Material Quality_S” belong to “material availability” precondition category and totally result in 0.1923 bits of information gain. Considering the overall uncertainty of making-do in China, 0.9551 bits (first row of column 4 in Table 5.5), the contribution of this precondition to overall uncertainty reduction in making-do is equal to 0.1923/0.9551 = 20%.
Figure 5.4. Uncertainty reduction in making-do knowing managers’ experienced delay
Figure 5.5. Contribution of precondition categories to making-do

Figure 5.5(a) shows that in China, availability of materials, design and specifications, and labor are the top-three preconditions influencing manager’s making-do decisions. Also,
Figure 5.5(a) shows that 53% of uncertainty in making-do could not be explained by the amount of delay Chinese managers have experienced in the past due to lack of readiness in preconditions. The remaining uncertainty about whether a Chinese manager is going to practice making-do or not depends on other factors such as owner request, crew utilization, etc. that were discussed in the literature review section.

The same interpretation applies for preconditions influencing making-do in the U.S. (Figure 5.5(b)). As was expected from the results in the previous section, the main precondition that determines whether a manager or crew-leader practices making-do or not is the “availability of design and working method instructions.” Also, comparing to China, preconditions readiness contributes more (8% more) in manager/crew leader’s making-do decisions since 45% uncertainty is left after the U.S. managers’ experienced delay is uncovered (compared to 53% in China).

5.6 Conclusions

In order to understand how the amount of task starting time and duration delay experienced by managers with different culture background influence their making-do decisions, this research conducted two surveys in China and the U.S. Findings showed Chinese project managers are less likely to decide making-do (62% chance) compared to their U.S. counterpart (77% chance). This could be related to the fact that making-do in China results in duration waste. Project managers in China, who prefer making-do in situations where “material”, “labor”, “equipment” are not ready and the “management/information flow” system is ineffective, have experienced on average two times more delay than the project managers who preferred to wait for preconditions to become ready. While in the U.S. the results are completely opposite and project managers who preferred making-do have
experienced up to 60% less duration delay due to the causes of delay that fall mainly into “design availability” and “labor availability” precondition categories. By utilizing RF and entropy-based Decision Tree, the research found that “material availability”, “detail design and working method availability”, and “labor availability” are the top-three preconditions that contribute 20%, 17%, and 4% to managers’ making-do decision in China. While in the U.S. the top-three preconditions are “detail design and working method availability”, “prerequisite readiness”, and “management/information flow”, which contribute 28%, 10%, and 9% to managers’ making-do decisions.

It should be noted that the survey in China was only conducted in one province, while the survey in the U.S. was nationwide. However, ShanDong province is the second most populous province and had the third highest GDP in China in 2017. In addition, the scope of this research is limited to government projects performed by civilian contractors in China and the U.S. Future research can perform more in-depth analysis to find out how ready is ready enough from Chinese and the U.S. project managers’ perspectives. Future findings will be highly valuable in terms of understanding to what extent making-do thresholds are different in different cultures.
CHAPTER 6. SUMMARY AND CONCLUSIONS

6.1 Summary

Previous research has emphasized the importance of increasing workflow reliability in construction projects. However, there was little research available to quantify benefit of having a highly-reliable workflow in a project, both from general contractors’ and subcontractors’ points of view. This is especially important to motivate and sustain collaboration as it answers the question “What is the benefit for myself vs. to the entire project when I devote more effort in planning?” Chapter 2 of this dissertation answered this question by developing a benefit allocation model based on game theory framework to distribute the benefit of highly-reliable workflow in a fair and efficient manner among subcontractors.

Although there is a massive body of knowledge addressing both constraints removal and workflow reliability, there was only a handful of research available that scientifically studied site-level planning which takes place during construction planning meetings. Also, there was little research available in the construction management literature quantifying information gain and exchange in construction meetings. To fill in the gaps in the body of knowledge, this dissertation studied construction weekly planning meetings’ discussions using 18 weeks of meeting minutes and developed strategies to improve the efficiency of planning meetings. In the Chapters 3, the researcher developed a methodology based on information theory to find out the important constraints and the order of addressing them during meetings with respect to workflow reliability.

After determining the value of highly-reliable workplans (Chapter 2), and how to create those (Chapter 3), the remaining chapters focused on identifying the barriers for executing a workplan. A similar research to the Chapter 4 of this dissertation was conducted by author’s
research group in 2011 and in the United States (Wambeke et al. 2011). This research compared and contrasted prevalent causes of delay and their underlying factor structure in China and U.S. and developed strategies to help international contractors in adjusting their policies of addressing causes of task delay based on their project portfolio (objective 3), determining the preconditions that are important to a manager’s decision of practicing making-do (to start a work without availability of its required preconditions) (objective 4).

The key findings of this dissertation are listed below in Table 5.1.

<table>
<thead>
<tr>
<th>Research Objectives</th>
<th>Conclusions/Key Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Benefit of Highly-reliable Planning</strong></td>
<td>Simulation Model of Subcontractor Trades:</td>
</tr>
<tr>
<td></td>
<td>1- Subcontractors’ horizontal partnering in performing HRP results in their incremental benefits.</td>
</tr>
<tr>
<td></td>
<td>2- Having more subcontractors makes short-term partnering more valuable and subcontractors can achieve more benefits form HRP.</td>
</tr>
<tr>
<td></td>
<td>3- Traditional benefit-allocation models have some drawbacks and cannot be accepted as fair, efficient, and stable schemes for sharing the benefits of HRP.</td>
</tr>
<tr>
<td><strong>2. Constraints Removal in Weekly Planning Meetings</strong></td>
<td>Bridge Construction Project Case Study:</td>
</tr>
<tr>
<td></td>
<td>1- Results showed weekly planning meetings work best to resolve constraints related to “equipment availability”, “design and working method clarification”, and “prerequisite work readiness” in order to increase workflow reliability.</td>
</tr>
<tr>
<td></td>
<td>2- Removal of these three constraints could help PPC improvement by almost 14%.</td>
</tr>
<tr>
<td></td>
<td>3- Using Chow-Liu tree greedy algorithm to prioritize constraints removal discussions results in quicker information gain for removing uncertainty in PPC.</td>
</tr>
</tbody>
</table>
Survey to study task variation in China and the U.S.

1- The top causes of starting time delay in China were ‘Permit to Start a Task’, ‘Lack of Labor (i.e. due to Harvest Season)’, ‘Design Change’, and ‘Wait to get Answer to your Design Questions’, which were identified as top-five causes of task starting time variation by respondents in three different position levels: executive managers, middle-level managers, and labor/crews.

2- Findings revealed ‘Permit to Start a Task’, ‘Lack of Labor (i.e. due to Harvest Season)’, ‘Design Change’ are also the main contributors to the task duration delay in China as well as ‘Constructability’ and ‘Plan Adjust (i.e. Scope Change)’.

3- None of the identified prevalent causes of task duration delay in China were the major concern of respondents in the U.S. with respect to the task duration delay.


5- There were six underlying factors responsible for covariation in experienced amount of task starting time and duration delay due to the 44 preidentified causes. These factors were: (1) Communication, Leadership, and Mgmt., (2) Design and Specs, (3) Hand Tools and Transportation, (4) Labor and Material Availability, (5) Space and Layout, and (6) Material Quality.

6- “Communication, Leadership, and Mgmt.” was the least different factor for task starting time and duration variation comparing China and the U.S. “Material Quality” was the most different.

Table 6.1. (continued).

<table>
<thead>
<tr>
<th>3. Prevalent Causes of Task Variation in China in Compared to the U.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey to study task variation in China and the U.S.</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>3- None of the identified prevalent causes of task duration delay in China were the major concern of respondents in the U.S. with respect to the task duration delay.</td>
</tr>
<tr>
<td>5- There were six underlying factors responsible for covariation in experienced amount of task starting time and duration delay due to the 44 preidentified causes. These factors were: (1) Communication, Leadership, and Mgmt., (2) Design and Specs, (3) Hand Tools and Transportation, (4) Labor and Material Availability, (5) Space and Layout, and (6) Material Quality.</td>
</tr>
<tr>
<td>6- “Communication, Leadership, and Mgmt.” was the least different factor for task starting time and duration variation comparing China and the U.S. “Material Quality” was the most different.</td>
</tr>
</tbody>
</table>
### 4. Factors Affecting Making-do in China and the U.S.

Survey to study making-do in China and the U.S.

1. Chinese construction managers who start the work disregarding the precondition readiness may experience up to two times more duration delay during the activity execution compared to those construction workers who prefer to wait for preconditions to become ready before commencing the work.

2. U.S. construction managers who start the work before all preconditions get fully ready may experience up to 60% less duration delay compared to the workers who wait for preconditions to become ready before commencing the work.

3. In China, “material availability” is the most important precondition that contributes to managers’ choice of making-do. Knowing the amount of delay experienced by a manager due to the causes of delay in this precondition category can reduce uncertainty in the manager’s choice of making-do by 20%.

4. In the U.S., “availability of detailed design and working method instruction” is the most important precondition that contributes to managers’ choice of making-do. Knowing the amount of delay experienced by a manager due to the causes of delay in this precondition category can reduce uncertainty in the manager’s choice of making-do by 28%.

### 6.2 Conclusions

With respect to contributions to the body of knowledge related to improvement of workflow reliability within construction projects, as well as the broader impact that has on the construction industry and beyond, this research:

- Identified and quantified the most prevalent causes of delay associated with construction projects in China based on the perspectives of workers, foremen, and project managers.
• Has shown the value of emerging analytical technologies, which have made it possible to analyze a large-scale unbalanced data, to simulate complexity of construction trades network, where fault-tolerant and lean performance must be achieved through the cooperation and coordination of those involved.

• Was the first of its kind with regard to using information theory to examine the efficiency of information exchange during meetings. (Thus, it will provide a deeper understanding of the relationship between humans’ decision-making factors and project performance factors, which will advance understanding in both human and engineering factors.)

• Provided a means to prioritize which constraints posed the greatest risk to project performance based on their mutual information with workflow reliability.

• Has a broad application in supply chains, disaster planning, communication networks, security, etc. and a variety of sectors and industries including public education, highways, water supply, real estate, manufacturing, etc. which could be potential beneficiaries of this research.

• Will significantly advance our ability to provide decision support systems that can adapt, self-organize, parameterize, and respond to the various construction environments.

• Has demonstrated how to extract useful information from the complex nature of a construction project where hundreds of factors can impact construction managers’ decision-making.

• Provides the framework and repeatable analytical methods to identify, prioritize, and increase workflow reliability in construction projects.
6.3 Limitations and Recommendations for Future Research

The future studies can address the existing limitations in each chapter of this dissertation to expand the current research.

Although simulation models often differ from practice, as they always include simplifying assumptions, they can be tweaked to better represent the existing process/operation. For example, subcontractors in the simulation model built in Chapter 2 of this dissertation lacked the power of decision-making based on their existing performance. In the real-world, however, subcontractors intentionally adjust their capacity to achieve high utilization of their crew. Future studies can add this feature to work by combining System Dynamics (SD) and Discrete-event Simulation (DES) modeling.

In Chapter 3, the case study was based on a project with less than 5% subcontractor performed. While the methodology should be widely applicable, the specific conclusions are case specific. The classification of meeting minutes in Chapter 3 was done manually because of project-specific limitations. Future studies, however, can automate the process of meeting discussion classification by utilizing advanced text mining methods. Also, it should be noted that some discussions during weekly planning meetings (such as deciding on working methods) could impact the workflow reliability in the long run, and their impact is not measurable by the PPC of the following week after meetings were conducted. Therefore, it is possible that results using proposed methodology underemphasize the value of some constraints removal discussions. Future research can extend the time frame for PPC to address this limitation.

In Chapters 4 and 5 of this dissertation, data in China was collected from government projects in a specific province of China. Collecting data in a broader scope, similar to data
collection in the U.S. by Wambeke et al. (2011), will help to better understand the prevalent causes of task starting time and duration delay in China. Also, this research expended less effort in investigating remedies for eliminating/addressing the prevalent causes of delay. However, current findings will help future researchers to direct their efforts for accomplishing this goal. Instead of studying 44-50 potential causes of delay, scholars can conduct in-depth future research on how to address/eliminate the prevalent causes of delay in China and in the U.S.
REFERENCES


APPENDIX A. VARIATION SURVEY

Thank you for taking the time to complete this survey. You probably need 30 minutes to complete. Please choose the answer that you think is most appropriate based on your experience with previous projects. The answer is for research purposes only. Your name work unit, and project name are kept confidential, because the above is not included in the survey.

The project mentioned in the following questionnaire refers to the project you have most recently completed. Please fill in the duration of this project.

Month / year

Background (please draw the appropriate options. If there is no suitable option, please fill in your answer on the blank line)

1. In which provinces have you worked on projects? Please check the corresponding place.

<table>
<thead>
<tr>
<th>Beijing</th>
<th>Tianjin</th>
<th>Hebei</th>
<th>Shanxi</th>
<th>Hunan</th>
<th>Guangxi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jilin</td>
<td>Heilongjiang</td>
<td>Shanghai</td>
<td>Jiangsu</td>
<td>Zhejiang</td>
<td>Chongqing</td>
</tr>
<tr>
<td>Fujian</td>
<td>Jiangxi</td>
<td>Shandong</td>
<td>Henan</td>
<td>Hubei</td>
<td>Guizhou</td>
</tr>
<tr>
<td>Yunnan</td>
<td>Tibet</td>
<td>Shaanxi</td>
<td>Gansu</td>
<td>Qinghai</td>
<td>Ningxia</td>
</tr>
<tr>
<td>Liaoning</td>
<td>Guangdong</td>
<td>Anhui</td>
<td>Hainan</td>
<td>Xinjiang</td>
<td>Sichuan</td>
</tr>
<tr>
<td>Inner Mongolia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. In which region of ShanDong province you have done projects? Please check the corresponding place.

<table>
<thead>
<tr>
<th>Qingdao</th>
<th>Jinan</th>
<th>Zibo</th>
<th>Zaozhuang</th>
<th>Dongying</th>
<th>Yantai</th>
<th>Binzhou</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weifang</td>
<td>Jining</td>
<td>Taian</td>
<td>Weihai</td>
<td>sunshine</td>
<td>Laiwu</td>
<td>Liaocheng</td>
</tr>
<tr>
<td>Texas</td>
<td>Linyi</td>
<td>Heze</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

154
3. What type of company do you work?
   A. owners (government owners)
   B. Unit owners (private owners)
   C. GC
   D. Subcontractors
   E. Engineering Firm
   F. Consultant Company (more for oversee the management)
   G. Labor company
   H. Labor/crew
   I. Agent Construction Company
   J. Other (please fill in)

4. How many people in your company?
   A. 25 or less
   B. 25 - 150 people
   C. 151-300 people
   D. 301-500 people
   E. 501-1000 people
   F. 1001-1500 people
   G. 1501-2000 people
   H. More than 2000 people
   I. __________________________people

5. How much is the annual revenue of your company (all in Chinese Yuan)?
   A. <1M
   B. 1-5M
C. 5M-30M
D. 30M-100M
E. 100-500M
F. 500M-2000M
G. 2000M-5000M
H. 5000M-10,000M
I. 10,000M-20,000M
G. 20,000M-50,000M
H. 50,000M-100,000M
I. ________________

6. The average size of project you work is how much?
   A. Less than 1 million
   B. 1-3 million
   C. 3M-10M
   D. 10M-30M
   E. 30M-100 million
   F. 100M-300 million
   G. 300M-1000M
   H. Billion or more
   I. Other __

7. What is the percentage of government projects in your company’s total project? __%

8. Your company currently has how many projects under construction at the same time?

9. For your project currently under construction, when material, personnel, machinery is not fully ready, you tend to choose A or B?
A. Start work
B. Waiting

No matter you chose A or B, what is the probability you do it that way __%?

10. What is your current job responsibilities?

A. Chief Engineer
B. Project Manager (more on admin)
C. Project Chief Engineer (Tech)
D. Consultant Engineer
E. Installation Engineer
F. Labor Company employees
G. Safety officer, technician, etc. management team
H. Foremen
I. worker
J. Other __

11. Your specialty?

A. Civil Engineer
B. Equipment Management Engineer
C. Survey Engineer
D. Other __

12. How many years you have been in construction industry? __

How many years you are at the current position____________________year

13. Your age?

A. 20-30 years old
B. 30-40 years old
C. 40-50 years old
D. 50-60 years old

14. What is your education level?
   A. primary school
   B. junior high school
   C. high school
   D. University
   E. graduate degree

15. Which province are you from? __

16. Why did you choose the construction industry? (Multiple choices are possible)
   A. personal interest
   B. acquaintance introduction
   C. is easy to master
   D. income is high
   E. professional choice
   F. other __

17. On average how many days you work per week? __

   On average, how many hours you work per day?

18. For the most recently completed project, how many managers you have? __

   How many site workers you have? __

The following question questionnaire involving eight major categories, please according to their size and influence of the sort of task start time for the duration of the project, 1 representative of the largest impact, 8 represents the minimal impact.
<table>
<thead>
<tr>
<th>Prerequisites</th>
<th>Start time delay (days)</th>
<th>Number of people affected by the start time delay</th>
<th>Project duration extension (days)</th>
<th>Number of people to ensure an increase in construction period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay in Project kickoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handoff of prerequisites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality check or approval of prerequisites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>other factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Design issues and construction process issues

<table>
<thead>
<tr>
<th>Consideration of constructability in Design (high construction quality requirements, construction difficulty, process and construction organization is</th>
<th>Start time delay (hours)</th>
<th>Number of people affected by the start time delay</th>
<th>Project duration extension (days)</th>
<th>Number of people to ensure an increase in construction period</th>
</tr>
</thead>
</table>
difficult )

<table>
<thead>
<tr>
<th>Design change</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Insufficient design drawings before starting construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Owner’s response time is too long</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consulting engineer reply time is too long</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Details and nodes in the construction drawing are not clear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex structure (e.g., non-standard layer)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The specific construction method instructions are not clear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Labor force

<table>
<thead>
<tr>
<th></th>
<th>Start time delay (hours)</th>
<th>Number of people affected by the start time delay</th>
<th>Project duration extension (days)</th>
<th>Number of people to ensure an increase in construction period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer harvest, autumn harvest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workers were called out to other project</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not enough people</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unstable staff</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inexperienced/newbie</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

19. Have you had the experience of being called to another project from a midway? If you have any, please choose the following reasons.
A. never
B. has been assigned several jobs at the same time.
C. influences from other trades (coordination problem)
D. period adjustment
F. plan is not coordinated
G. Other

20. Have you participated in training outside this position?
   A. Yes
   B. No
   C. Not sure

21. Do you participate in skills training?
   A. Yes
   B. No
   If No is selected, skip questions next two questions

22. What kind of skills training have you received? ___ (please fill in)
    How much time has it been trained? ___ (please fill in)

23. Who will bear the training costs? ___ (please fill in)
    A. company
    B. person
    C. Other (please fill in)

Tools and equipment
<table>
<thead>
<tr>
<th>Construction</th>
<th>Start time delay (hours)</th>
<th>Number of people affected by the start time delay</th>
<th>Project duration extension (days)</th>
<th>Number of people to ensure an increase in construction period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower crane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand operated tools</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other vertical transport machinery</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal transport machinery</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

24. Do you often wait for the construction elevator? If yes, please choose from the following reasons.

   A does not need to wait
   B elevator is empty, but the operator is not
   C elevators and operators are there, but it is not my turn yet
   D elevator is occupied
   E repair
   F Other___________________________________________ (please fill in)

25. Do you often need to wait for small machines? If yes, why?

   A does not need to wait because everyone has one small machine
   B has not been trained and will not be used
   C tool is not enough
   D can't find tools or lose
   F repair
G Other______________________________ (please fill in)

26. Do you often wait for the tower crane? If yes, please choose from the following reasons.

A. does not need to wait Tower
B. is empty, but the operator is not
C. tower crane and operator are there, but need to wait in line
D. tower crane is occupied
E. repair
F. Other______________________________ (please fill in)

27. Do you often need to wait for manual tools? __

If yes, why? __

A does not need to wait because one person
B tool is not enough
C could not find the tool or lost
D maintenance
F Other______________________________ (please fill in)

<table>
<thead>
<tr>
<th>Material</th>
<th>Start time delay (hours)</th>
<th>Number of people affected by the start time delay</th>
<th>Project duration extension (days)</th>
<th>Number of people to ensure an increase in construction period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material was moved twice</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material is not on time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply material does not match</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
28. You need to wait for material handling twice? If so, please choose from the following reasons.
   A. does not need to wait
   B. has no equipment and operator for handling
   C. does not have a turn
   D. the schedule was not coordinated
   F. repair
   G. material yard is too far
   H. other

29. Do you need to wait for the material to enter the market? If so, please choose from the following reasons.
   A. does not need to wait Delay caused by
   B. supplier
   C. progress ahead leads to material shortage
   D. construction plan changes
   E. material scheduling is not planned
   F. other

30. Do you often need other supplies? If yes, why?
   A. does not need to wait
   B. field supplies are not enough
   C. incomplete plans
   D. other

31. Do you often encounter material size wrong? If yes, choose from the following reasons
32. Do you often encounter material type errors? If yes, choose from the following reasons

A. did not touch  
B. manufacturer error  
C. design problem  
D. other  

On-site issues

<table>
<thead>
<tr>
<th>Issue</th>
<th>Start time delay (hours)</th>
<th>Number of people affected by the start time delay</th>
<th>Project duration extension (days)</th>
<th>Number of people to ensure an increase in construction period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited space available</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hard to reach the work surface</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Layout is inconvenient, restricted field around</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor traffic Conditions in the field</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

33. Are you experiencing delays caused by overcrowded scene? If yes, please select the reason

A. did not encounter  
B. This is inevitable
C. because other work is advanced or delayed  
D. because of the compression of the period  
E. comprehensive plan is not well planned  
F. other

Management issues

<table>
<thead>
<tr>
<th>Management issue</th>
<th>Start time delay (hours)</th>
<th>Number of people affected by the start time delay</th>
<th>Project duration extension (days)</th>
<th>Number of people to ensure an increase in construction period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Questions about design issues cannot be answered in time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geological survey does not match actual conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Did not get guidance from the supervisor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insufficient management staff field</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordination between different types of work</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over commitment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Team leader is not high in management ability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan adjustment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Team leader has insufficient communication skills</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Owner, design and construction communication is not smooth</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor communication within the construction unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>other</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

34. Owners of instructions how to reach your hands?

A. Owner --- you  
B. Owner --- design unit or general package --- you  
C. Owner --- design Unit or General Package --- Labor Service --- You  
D. Owner --- design unit or general package --- subcontractor --- you

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E. Owner --- design Unit or General Package --- subcontracting Unit --- Labor Service Company --- You

F. Owner --- design unit or general package --- subcontracting unit --- subordinate subcontracting unit --- you

35. How often do you get instructions from their superiors? (eg what to do every day, what to do weekly, project schedule, work method)

A. never
B. once a month
C. 2 - 3 times a month
D. once a week
E. 2-3 times a week
F. once a day
G. other

36. Your supervisor is usually willing to listen to subordinates recommendations on working methods and processes it?

A. is not willing
B. listened, but did not adopt
C. listened, and adopted
D. listened, partially adopted

Weather and objective factors

<table>
<thead>
<tr>
<th>Start time delay (hours)</th>
<th>Number of people affected by the start time delay</th>
<th>Project duration extension (days)</th>
<th>Number of people to ensure an increase in construction</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>
Weather (too cold, too hot, rainy, windy)  
Objective factors (uncontrollable factors such as traffic control, noise control, night construction and environmental management)  
other