ABSTRACT

WAMBEKE, BRAD WILLIAM. Identifying, Prioritizing, and Reducing Variation of Construction Related Tasks. (Under the direction of Dr. Min Liu and Dr. Simon M. Hsiang).

In this research, variation is defined as the time difference between what was planned and what occurred in terms of task starting times and duration. Variation in construction tasks is important as it can impact overall productivity performance. Construction projects consist of a large number of interdependent tasks. When the starting time or duration of one task varies, it can affect other downstream tasks and result in disruptions to the schedule and/or decreased productivity. The construction process is complicated and involves numerous people with different levels of responsibility, which can make identifying the root causes of the variation difficult. The primary goals for this research include identifying, prioritizing, and reducing variation of construction tasks. Identification involved determining the most prevalent root causes of variation. Factor analysis was utilized to illustrate how those individual causes were interrelated with one another. A risk assessment matrix, commonly used in military planning, was used to quantify the associated frequency and severity of the causes of variation and prioritize which causes posed the greatest threat to project performance. Social network analysis was conducted to identify the underlying network of trades, along with the key members of the network. The results of the variation and social network analyses were combined to develop a decision support system to target variation for elimination. The analytical hierarch process (AHP) was used to support decision making when multiple and conflicting criteria were involved. Lastly, the research examined the feasibility of reducing variation by using the

Last Planner System®. This research is important and valuable as it serves to address several gaps in the body of knowledge pertaining to variation associated with a construction project. Additionally, this research has a broader impact on the construction community. It provides a framework and repeatable associated analytical methods to identify, prioritize, and reduce variation on a construction project.

Identifying, Prioritizing, and Reducing Variation of Construction Related Tasks

by
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DEDICATION

This work is dedicated to my wife and children. Without their love, sacrifice, patience, and support during the past three years, this would not have been possible.

BIOGRAPHY

I am currently a lieutenant colonel in the US Army and have had the distinct honor and privilege to serve among some of the finest men and women of our country for the past 18 years. I have also been fortunate for the opportunity to pursue my PhD. With great reward, comes great responsibility. I will command a battalion of approximately 900 Soliders following graduation. Upon completion of command, I will serve the remainder of my military career as a permanent academy professor in the Civil and Mechanical Engineering Department at the United States Military Academy, West Point.

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CHAPTER 1

1.0 INTRODUCTION

Variation, defined for this research as the difference between what was planned and what occurred always exists in the construction work process. Variation can be considered a form of waste and it can have a significant impact on labor productivity and can pose challenges to project managers. There are three facets of this research. The study was conducted to identify the most prevalent causes of variation, develop techniques to prioritize those causes based on risk in terms of frequency and severity, and examining how to reduce or eliminate the variation. Construction project tasks for this research are focused on the daily activities associated with the weekly work plan.

1.1 Background

Construction is a labor intensive industry, and labor related costs often account for a large percentage of the total costs for a construction project. For example, the labor component for electrical and mechanical construction has been estimated to be 40-60% (Hanna et al., 2002). Gomar et al. (2002) found it was not uncommon for labor costs to account for 30-50% of the total project cost. Given the high percentage of the overall project cost, it is important to recognize the factors that impact labor productivity and costs and to improve control when feasible.

Variation almost always exists in the construction work process and it inevitably can have a significant impact on labor productivity, yet the root causes of variability often remain unclear. Variation can result from uncertainty and can be viewed as a form of waste.

Uncertainty (Uncertainty, 2011) refers to being in a state of doubt or being dependent on chance. Crichton et al. (1966) found uncertainty to be one of the greatest challenges to the interdependent building process. Uncertainties can stem from numerous sources ranging from items like labor, equipment, and materials, to government departments, planning authorities, and even the general public (Crichton et al. 1966). For example, there may be uncertainty as to whether or not a shipment of materials will arrive when anticipated. When the materials do not arrive as anticipated and scheduled tasks are impacted, it causes variation. Variation, at least when it causes a delay, can thus be considered a form of waste as it can impact schedule reliability and productivity.

Ballard (2000) used the percentage planned complete (PPC) to examine work plan reliability. The PPC is the ratio of the number of tasks 100% completed to the number of tasks planned. Ballard's research (2000) indicated an average PPC of 54%, thus illustrating the extent of variation in construction. Previous research, which is discussed in further detail in the literature review section, has demonstrated the importance of variation. Howell and Ballard (1994) discussed the importance of reducing variation to stabilize work flow. Howell et al. (2001) demonstrated that reducing variation to improve planning reliability from 50% to 70% can theoretically increase productivity by 30% (i.e. from 50% to 65%). Thomas et al. (2002) found labor force variability was strongly correlated to improved performance. Despite the previous research about the presence and importance of variation in construction, little work has been done to identify the root causes of variation and how they correlate to each other.

Additionally, little research exists that examines systematic means of prioritizing causes of variation for reduction or elimination during the planning process. Prioritizing the causes of variation to be targeted for reduction is important for managers as it enables them to get the "biggest bang for the buck." In other words, they can focus their efforts on eliminating the cause(s) of variation that will provide the greatest benefit in terms of project performance. A critical assumption in this study is that the capacity for root cause analysis and preventive action is limited, and it is not feasible to address all causes of variation simultaneously. This research uses a risk assessment matrix (Figure 1.1) to analyze the risk due to variation. Risk assessment matrices, commonly used in military planning, consider both the likelihood a particular event will occur and the associated severity if that event does occur (FM 100-14, 1998). The resulting risk, illustrated as low, moderate, high, and extremely high in Figure 1.1, can then be prioritized for mitigation or elimination.

		Frequency or Likelihood				
		Rare	Unlikely	Possible	Likely	Certain
Severity	Catastrophic	M	H	E	E	E
	Major	M	H	H	E	E
	Moderate	L	M	H	H	E
	Minor	L	L	M	H	H
	Low	L	L	L	M	M

Key: L=Low; M=Moderate; H=High; E=Extremely High

Figure 1.1: Risk Assessment Matrix

Construction projects are often complex and full of variability and uncertainty in interdependent tasks that project managers work to synchronize to the best of their ability. When one task experiences variation, it may cause another task to experience variation as well due to interdependency. This interdependency poses a challenge to project managers as they try to deal with scheduling and sequencing a large number of trades involved with a project. Plausibly and arguably, there is an underlying social network of trades that exists and recognizing it can help succeed in this challenging environment. A social network is pattern of ties that exist between different entities (i.e. people, organizations, countries, etc.). In construction, it is arguable that a good superintendent who understands the underlying social network of trades is one key to the success of a project. It takes years of experience to develop this skill and according to the interviews conducted by the researcher, few superintendents could articulate the social network even though they knew it existed. This research incorporates the use of social network analysis to try to identify these networks as well as the key trades in a particular project.

Once the causes of variation and the associated key trades are identified, a project manager can focus their planning efforts to target and reduce the variation and improve project performance. There are likely to be multiple factors that influence the decision as to how to reduce the variation; therefore, a systematic method approach that incorporates these factors is needed to assist with the decision process. This research examines the feasibility of using the LPS® to reduce or eliminate those causes of variation deemed to pose the greatest risk to project performance. It also incorporates the analytical hierarchy process (AHP) when multi-criteria decisions need to be made.

1.2 Research Objectives

The primary focus of the research is on variation of construction project tasks. There are eight individual research objectives that support the overall framework and guide this research. The objectives focus on identifying the causes of variation, prioritizing which of those causes to reduce, and then examining how they can be reduced. These research objectives were studied and analyzed using a survey and three separate case studies. While each of these could be viewed as an independent research activity, they are related and together support the overall objectives of this dissertation. The survey was employed to identify the causes of variation and their impacts on productivity. The survey also served to create and prioritize factors to be considered during weekly work planning meetings, based on the number of trades involved. The case studies were conducted to gather empirical data and demonstrate how the variation could be identified, prioritized for reduction, and then reduced using the LPS®. Eight contributive objectives were developed to achieve the overall goad of this study.

Objective 1: Determine the most prevalent individual causes of variation and how workers, foremen, and project managers view the causes differently.

Objective 2: Identify underlying factors that correlate the individual causes of variation in terms of starting time and duration.

Objective 3: Determine the causes of variation that pose the greatest risk of impacting project performance.

Objective 4: Develop the organizational social network of trades for a given construction project.

Objective 5: Analyze the social network to identify the key trades within the network.

Objective 6: Identify the organizational structure of contractors / trades associated with the variation posing the greatest risk to project performance.

Objective 7: Develop a decision support system to target trades in an effort to reduce variation.

Objective 8: Compare performance in terms of productivity and cost savings for two similar projects, in which the LPS® was used on one, but not the other.

1.3 Research Design

1.3.1 Research Design Overview

There were two primary methods used to gather data in the research; the use of a survey and the execution of three case studies. Although the details of both are discussed in Chapter 3 (Methodology), a flow chart (Figure 1.2) and a brief narrative are provided as an overview of the research design.

The literature review served to identify what research has been done in terms of variation and its impact on productivity. A survey was then developed to identify the specific causes of variation and to examine their impacts on productivity. The results of the survey addressed the first two research objectives and helped to determine the direction for the remainder of the research. The natures of the causes of variation supported the study hypotheses that it is feasible to identify and remove causes of variation prior to buffering the variability that cannot be eliminated. Buffers can be considered to be a source of contingency used as a safety factor so a trade does not take longer to complete a task than planned. A benefit of reducing variation is to also reduce this contingency, which can result in reductions in cost or schedule. The case studies were performed to further validate the results of the survey and then to generate quantitative data associated with the weekly work plans of different construction projects. This data was used to address the remaining six research objectives.

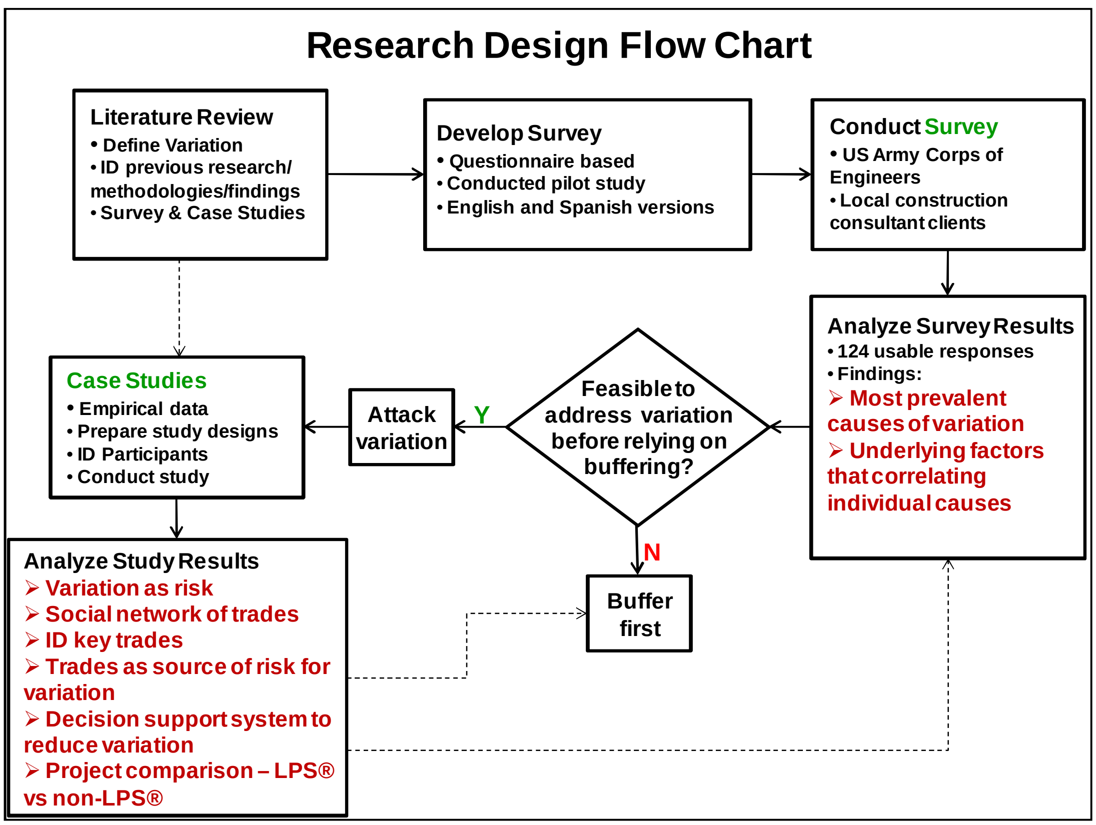


Figure 1.2: Research Design Flow Chart

1.3.2 Questionnaire Survey

The first stage of field work was to employ a nationwide survey to gather data about the specific causes of variation. The respondents for the survey were either working under a contract on a public project being managed by the US Army Corps of Engineers or they were a client of a local construction consulting company. The survey was intended to be distributed nationwide and both the Corps of Engineers and the consulting company had clients located throughout the United States. There were 124 usable responses to the survey, 80% of which came from contractors working for the Corps of Engineers and the other 20% from clients of the consulting company.

1.3.3 Case Studies

Meredith (1998) described the rational and case study research approaches. The rationalist method involves modeling by equations, laboratory experiments, and statistical survey analysis to *explain* what and how things happen. Case study research typically collects data from a natural setting, without experimental controls or manipulations. The goal of case study research is to *understand* what is happening and helps the researcher comprehend why certain characteristics or effects occur or do not occur. The objectives of this research were consistent with those of the case study approach; therefore, case studies were employed. Case studies can be single or multiple-case designs (Tellis, 1997). Although not required, multiple cases can strengthen the results by replicating the pattern-matching, thus increasing confidence in the robustness of the theory (Yin, 1994). In this research, a multi-case design, consisting of four studies, was used. The case studies further validated the survey results in terms of identifying the leading causes of variation. The case studies were also used to prioritize which causes of variation should be targeted for reduction and to examine if using the LPS® could effectively reduce the variation. The specifics of these studies are described in more detail in the methodology portion (Chapter 3); however, Table 1.1 below lists the three case studies and provides a general description of how they were used for this research.

Table 1.1: List of Case Study Participants

Case Study	Company ID	General Case Study Description
1	GC	A general contractor tracked variation in an effort to identify which causes of variation posed the greatest risk to project performance. Social network analysis was used to examine the organizational structure of trades associated with the variation. Lastly, a decision support system was used to develop a prioritization for reducing variation within the project.
2	SUB	A local mechanical contractor performed an internal study while executing two similar projects. The study identified which causes of variation posed the greatest risk to project performance. The LPS® was used on one of the projects to reduce the variation and a productivity benefit-cost analysis was performed to determine if using the LPS® was beneficial.
3	MR1 MR2	The study involved two companies, both which perform masonry restoration activities. One (MR1) used the LPS® and the other (MR2) did not. The case study was intended to examine differences in their performance while using different planning philosophies; however, one of the companies (MR2) did not provide data as planned. Therefore, the results of the study are limited by the information and observations obtained during a single site visit.

1.3.4 Analysis Techniques

As previously mentioned, there were two primary means to collect data. The approaches and techniques used to analyze the data differ for the two methods of data collection and are introduced here and are more fully described at the points where they are used in the dissertation.

- *Factor Analysis.* The survey involved collecting data about the perceptions that laborers, foremen, and project managers had in terms of what were the primary causes of variation. The research hypothesized that the individual factors were not independent and multicollinearity existed. SAS was used to perform factor analysis to further analyze the survey data with a goal of determining how the individual causes could be clustered together into a smaller number of factors.
- *Social Network Analysis (SNA).* Just as the individual causes of variation are not all independent, nor are the trades. There is an underlying social network of trades that exists within a construction project. SNA was conducted to identify this network for a given project.
- *Analytical Hierarchy Process (AHP).* There were instances when multiple criteria need to be considered when making a decision. The AHP was used as a means to assist with the decision making process in the study.
- *Benefit / Cost Ratio Analysis.* Despite all of the various analysis methods, money is one of the key factors that comes into the decision making process. A benefit / cost analysis

was conducted with the 2nd case study while examining the use of the LPS® to reduce variation and improve project productivity.

1.4 Motivation / Research Significance

My motivation for this research is twofold. First, I feel construction engineering and management is an important and essential aspect of the construction industry and I want my research to be worthy addition to the construction related body of knowledge. Second, I want my research to have a practical use to the construction industry. My hope was that companies that assisted or were involved with my research would be able to directly learn and improve as a result of my work. I chose the topic of variation as I feel it is an area within the construction industry that requires additional research and that the new knowledge gained will be useful to those who are in academia and to those who work in the construction industry.

Research has been conducted on factors affecting productivity and on variation. As will be discussed further in the literature review chapter, there are different views pertaining to variation. Some argue that variation is uncontrollable [Radosavljevic and Horner (2002)]; some argue it is better to use buffers to remain flexible in an attempt to address variation [Thomas et al. (2002)]; while some argue it is best to try to eliminate variation where possible before buffering what cannot be eliminated [Howell et al. (1994)]. Although there is a significant amount of research on variation and productivity independently, there is minimal research directed at understanding the root causes of variation and examining how this variation can be reduced. There is also little research focused at prioritizing which causes of variation, along with their associated trades, that pose the greatest risk to project performance. Lastly, there is little empirical data to support whether or not it is feasible to use additional planning to effectively reduce variation while achieving an acceptable benefit to planning cost ratio. This research was intended to help fill these gaps in the body of knowledge pertaining to variation of weekly work plans and should be useful to project managers as they strive to improve project performance.

1.5 Scope Limitations

Respondents to the survey were volunteers of companies that were working under a contract for the Corps of Engineers or were a client of a local construction consulting company, therefore the data is limited to their input.

Although efforts were made to involve similar type projects for the case studies to compare to one another, all aspects of the projects were not identical. The case studies were limited to the types of projects that the companies participating had planned and were executing. One of the case studies involved a general contractor with multiple subcontractors. Another case study involved just a mechanical contractor; therefore, this research does not cover all the different types of construction projects. However, the research results are still relevant and the research methods are repeatable and can be applied to other types of projects with minimal adjustment.

CHAPTER 2

2.0 LITERATURE REVIEW

The purposes of this literature review are to study the background of construction research pertaining to variation, variability, and variance, to define variation for this research and to identify causes of variation and their relation to work flow and productivity. Another purpose of the literature review is to study research pertaining to factors affecting productivity as they are hypothesized to be associated with factors causing variation. The planning philosophies associated with Lean Construction are measured as part of the case study; therefore Lean Construction was also studied as part of this literature review. Lastly, factor analysis, social network analysis, and the analytical hierarchy process (AHP) were used in this research; therefore, the backgrounds of each area, as they pertain to construction, are included in the literature review.

2.1 Construction Research Pertaining to Variation, Variability, and Variance

2.1.1 Definition of Variation

There are several different definitions of variability or variation as it pertains to labor productivity. Rilett (1998) defined variability as the variance associated with a component or end product specification in construction projects. Tommelein et al. (1999) defined work flow variability as the standard deviation from an expected average. Radosavljevic and Horner (2002) defined variance in construction labor productivity as standard deviation, a measure of dispersion from the mean. Thomas et al. (2002) calculated variation of productivity as the average of the absolute value of the difference between daily productivity and the baseline productivity. Howell et al. (2004) measured variability of work flow by comparing the tasks assigned (those tasks that "will" be done), to those completed (what "did" get done). The PPC is the ratio of the number of tasks 100% completed to the number of tasks planned. It can be used to indicate work plan variability as shown in Equation 1 below. Koskela (2000) defined variability as random variation in the processing times or arrival of inputs. For this research, variation is defined as the difference in what was planned and what occurred in terms of either task starting time or task duration. This definition was selected for use because 1) the difference between planned and actual task starting times or duration impacts productivity performance significantly, and 2) this definition provides a direct means to measure the variation. This definition is also consistent with previous definitions used in construction research [Howell et al. (1994); Horman and Thomas (2005); Kaplan et al. (2005)].

$$PPC = \text{Number of tasks completed} / \text{Total number of tasks on weekly work plan} \qquad \text{Eq. 1}$$

This research studied two types of variation. They are starting time variation and task duration variation. The starting time variation is the difference between the planned and actual starting time of a task. The task duration variation is the difference between the planned and actual task duration. An example is provided to further illustrate these two types of variation.

Consider, for example, a crew scheduled to install sheetrock. They were scheduled to start work at 8:00 and the installation was planned to take eight hours to complete. If the crew started at 8:00, but it took nine hours to complete the installation, the starting time variation would be zero and the task duration variation would be one hour. The starting time and task duration are measured independently. Even if a task started at a different time than it was planned, the task duration variation could still be zero provided the actual duration was equal to the planned amount of time.

2.1.2 Research on Causes of Variation and Relationship to Work Flow and Productivity

Several researchers, although with somewhat opposing views, have identified variation as an important aspect of the construction process. Adherents of the opposing views would agree that variation cannot be entirely eliminated from the construction process, and hence provision must be made for flexibility in response to variation. One type of response is to buffer variation with inventory, capacity or time. Thomas et al. (2002) examined the relationship between construction output variability and labor performance based on concrete formwork field data from 14 projects. They used a factor resource model and a project waste index to examine the relationship between the variability of workflow and labor productivity. They concluded that labor force variability was more strongly correlated to improved project performance than was workflow variability. It should be noted that Thomas et al.'s (2002) definition of variability was more closely associated with that of standard deviation from a baseline value over time, rather than the definition expressed at the beginning of this paper. Based on their research, they recommended a strategy of flexibility (i.e. adjusting crew sizes and/or work hours or using alternative assignments) to deal with labor force variability, rather than using management action to reduce the causes of variation. Although Thomas el al.'s (2002) was based on concrete formwork activities, it was included in the literature review as the philosophy could also apply to other trades within the construction industry. Horman and Thomas (2005) performed an exploratory analysis of the relationship between inventory buffers and construction labor performance in order to identify whether optimal levels of inventory buffers could be observed for labor performance outcomes. They used a project waste index to study the size of the buffer between rebar fabrication and installation and compared it to the labor performance of the fabrication and installation crews for three commercial projects in Brazil. They concluded that some inventory buffer helped achieve the best labor performance and that the inventory buffer seemed to be related to construction labor performance. Although the causes of variation were not specified, the research demonstrated that variation is detrimental to project performance. Again, this view focused on buffering first, rather than reducing the causes of variation by some form of management action prior to buffering.

The opposing view is from those who think is it feasible and important to first reduce the variability to the extent possible, then buffer what cannot yet be eliminated. Howell et al. (1994) studied buffers, project performance, delivery of material, and the planning system to illustrate the importance of reducing variation. They used data associated with pipe design, fabrication, and installation. They concluded that flow variation could be reduced by stabilizing functions through which the work flows, from concept to completion.

They also concluded that planning systems must include a means to adjust what work "SHOULD" occur, so operations could better match that "WILL" get accomplished. Stabilizing work to create smooth continuous flow is consistent with the Toyota Production System (Ohno 1988). Reliable flow is also important when considering the impact on queuing.

Queuing theory is basically the study of waiting lines and a common use in construction has to do with earth moving operations (Farid and Koning 1994). Regardless of the activity, when variation exists, the queue and the entire process can potentially be affected.

Ballard and Howell (1998) used the percentage planned complete (PPC) to examine work plan reliability. The PPC is the ratio of the number of tasks 100% completed to the number of tasks planned. Ballard and Howell's (1998) research indicated an average PPC of 54% for over 450 weeks' worth of data; thus illustrating variation is certainly present in the construction industry. As a result, Ballard created the LPS®, in which the last planner (typically the foreman) develops the weekly work plan by using a 6 week look-ahead process to ensure constraints on successful task execution are identified and removed. If the constraint cannot be removed, the task is not available to be included on weekly work plans. The intent of the LPS® is to create a more reliable weekly work plan. Howell et al. (2001) demonstrated that reducing variation to improve planning reliability from 50% to 70% can theoretically increase productivity by 30% (i.e. from 50% to 65%). Liu and Ballard (2009) demonstrated use of the LPS® can increase both the PPC and productivity as well.

Table 2.1 summarizes much of the research that has been performed in terms of defining variation, variability, and variance. It also highlights the research objectives, conclusions and remaining questions. Based on the literature review, there is a gap in knowledge in terms of identifying the root causes of variation. This research assumes factors causing variation are related to, and the same in many cases, as those that affect productivity. Although little research is focused at identifying the root causes of variation, there has been a significant amount of research aimed at factors affecting productivity. Section 2.2 provides information pertaining to the literature review on factors affecting productivity.

Table 2.1: Literature Review Summary for Variation, Variance, and Variability

Author/Reference	Term	Definition	Research OBJs	Research Design/Method	Conclusions	Remaining Questions
Howel et al. (1994)	Variation	Never clearly defined, but can be implied to be a difference from what was expected.	Provide suggestions for research and improved practice regarding the management and reduction of flow variation.	Use discussion of data regarding buffers, project performance, delivery of material, and the planning system to illustrate the importance of reducing variation.	Flow variation can be reduced by stabilizing all functions through which work flows from concept to completion. Planning systems must include a means to adjusting “SHOULD”, so operations can better match “SHOULD” with “WILL”.	What were the causes of the variation? How does the process of reducing variation differ between the different aspects - planning, design, fabrication, deliver, installation?
Rilett (1998)	Variability	$V_{T_{cl}} = \frac{\sum_{i=1}^{T_{cl}} (y_{cl_i} - \bar{y}_{cl})^2}{(T_{cl} - 1)}$	Develop a methodology for identifying variability in density measurements of pavement.	Considered three areas: 1) Contract Variation: Variability of density measurements from different contracts (projects). 2) Lot Variation: Variability of density measurements from same lot (i.e same specification). 3) Test Variation: Variability of samples between the two test methods used (Marshall or Field Density).	1) FD has higher variability than MD tests. 2) Larger variance between contracts than lots (as expected).	Should there be a specified or acceptable level of variability for the density? What are the root causes of the variability?
Tommelein et al. (1999)	Variability	Deviation from a mean value	Illustrate the impact work flow variability has on performance of construction trades and their successors.	Game - involving dice with different variability. Computer simulation model	Variable (unreliable) work flow results in 2 kinds of waste: 1) production stations cannot realize their full production capacity because they are starved for resources. 2) Intermediate buffers are larger when high variability prevails.	How tightly should we try to control vairation for different aspects of the construction industry? Some variation is not preventable - how much planning is enough / too much?
Thomas et al. (2002)	Variation	$V = \frac{1}{n}\sum\sqrt{(DailyValue - BaselineValue)^2}$ $CoeffOfVar = \frac{Vx100}{BaselineValue}$ $PWI = \frac{Cumulative - BaselineValue}{BaselineValue}$	Examine relationship between construction output variability and labor performance.	Test several measures of construction output variability against labor productivity.	Workflow variablity has little impact on performance. Labor force variablitiy more strongly correlated to improved performance. Recommends strategy of flexibility to deal with labor force variability (adj crew sizes, work hours, alt assignments).	What was planned? How much variation was there from what was planned? How do you identify the root causes of the variation? Without knowing these, it is hard to know where to focus efforts to reduce variation or if a strategy of flexibility is the best.
Radosavljevic and Horner (2002)	Variance	Standard deviation - measure of dispersion $S = \frac{1}{n-1}\sqrt{\sum_{i=1}^{n}\left(x_i^2 - \bar{x}^2\right)}$ Variance = S^2	Reveal evidence that normality (random behavior) is not a characteristic of productivity (i.e. show there is too much variability for the central tendency theory to apply).	Statistical analysis on productivity data sets (5 formwork & 7 masonry) from 11 different sites	Productivity data in study had stable mean, but unstable (undefined) variance	The specific productivity tasks were not mentioned, nor was the data broken down into categories (other than masonry or formwork related). What if the variance within like tasks is considered/examined? Is their conclusion still valid? What tasks experience the greatest variation? Seems that's where the focus should be.

Table 2.1 Continued

Author/Reference	Term	Definition	Research OBJs	Research Design/Method	Conclusions	Remaining Questions
Koskela (2004)	Variability	Random variation in the processing times or arrival of inputs	Analyze whether Lean Thinking can be viewed as a theory of lean production.	Assess Lean Thinking in terms of development of a theory.	Lean Thinking cannot be viewed as a valid and mature theory of production.	Is Lean Construction being build/developed as a theory or just a method to improve performance?
Howell et al. (2004)	Variability of Work-Flow	Measured by comparing the tasks assigned (what "Will" be done), to those completed (what "Did" get done)	Address issues/concerns with Thomas' paper "Reducing Variability in Improve Performance as a Lean Construction Principle."	Respond to another journal article	Authors should have condisered what was planned vs. what was completed to define the variation. Disagreed with the author's opinion that a flexible strategy is the best way to deal with variation of the labor force. Stated the authors (Thomas et al.) did not provide quantitative evidence to substantiate this claim.	N/A - commenting on another paper
Horman and Thomas (2005)	Variability	Implied to mean a change from what was expected.	Perform an exploratory analysis of the relationship between inventory buffers and construction labor performance. Identify whether optimal levels of inventory buffers can be observed for labor performance outcomes.	The size of the buffer between rebar fabrication and installation in the construction of a structural system is compared to the labor performance of the fabrication and installation crews.	Some buffer helps achieve the best labor performance in the construction operations studied. For the studied projects, inventory buffers seem to be related to construction labor performance.	What were the causes of variation - they were not identified or studied in this paper? How much of the variation could be accounted for by other means(better planning, etc.)?
Kaplan et al. (2005)	Variability	Never clearly defined, but can be implied to be a difference from what was expected.	Assess the presence of product and process variability in demand and supply, and the impact it has on precast pile delivery.	Elaborates on two deterministic scenarios and compares those with actual data from a project involving 340 precast piles. The performance of the system is analyzed on the basis of inventory vs. work completed.	Model 2 (Just in time) preferred: Less inventory - less handling and storage costs Less space - less capital investment More adaptable if project requirements change	What was the variability associated with the execution of installing the piles? Is it meaningful as the "causes" may be hard to determine if they are due to differences in ground conditions. How much waste is associated with the practice? How much site exploration is appropriate to have an adequate picture of the subsurface conditions...to further refine pile design?
Kim et al. (2008)	Variance Variation	Although never defined, variance can be implied to mean uncertainty, particularly in terms of cost estimation.	Develop a model to classify overseas construction projects into five cost performance groups: extreme cost overrun, moderate cost overrun, neutral, moderate cost saving, and extreme cost saving.	Used survey data to create a model using factor analysis correlated with cost performance data. Validated the model with bootstrap method (used original data to validate model)	The model helped predict the construction cost performance of a potential international project, with regard to the contractor's initial cost estimate.	Is there a plan to validate the model with data other than the original survey data?
Hallowell and Gambatese (2010)	Variation	Although never defined, variation can be implied to mean a difference.	To provide CEM researchers with a standard methodology for implementing the Delphi method in rigorous studies intended for publication.	1) Paper describes the traditional procedures required to conduct the research methodology as described in literature. 2) In an effort to create a standard and adaptable methodology with application to many types of CEM research, guidelines and minimum requirements for effective implementation of all phases of the Delphi process are presented.	Delphi Method has been used very little (only 8 studies) with CEM research. Significant variability between studies in terms of methodological approach	Although it was addressed in the article, isn't bias still a concern? How do you overcome it?

2.2 Construction Research Pertaining to Factors Affecting Productivity

A significant amount of research has been performed in reference to factors affecting construction productivity. The literature review used to develop a baseline of factors to consider when examining variation. Borcherding and Gardner (1981) identified material availability, tool availability, rework, overcrowded work areas, inspection delays, foreman incompetence, crew interference, crew turnover, and foremen changes as the top nine factors affecting productivity. Thomas and Yiakoumis (1987) categorized factors affecting productivity into four categories; environmental, site, management, and design factors. Herbsman and Ellis (1990) categorized specification, design, material, and location factors as technological influence factors. Additionally, production, social, and labor factors were categorized as organizational influence factors. Thomas and Sakarcan (1994) identified congestion, sequencing, weather, plant status, information, equipment, tools, material, rework, component size, specifications, design features, work content, and scope, as factors affecting productivity using a factor model. Portas and AbouRizk (1997) used an artificial neural network to predict low/medium/high productivity rates for concrete formwork. They found work complexity, superintendent skill, crew skill, design accuracy, dimensions, degree of repetition, working condition, site congestion, and site access as primary factors affecting productivity. Somnez and Rowings (1998) also considered factors associated with concrete placement activities and found quantity, job type, crew size, percent overtime, crew composition, weather, and the concrete pump to be the primary factors impacting productivity. Rojas and Aramvareekul (2003) found scheduling, manpower experience and motivation, adverse working conditions, and scope changes to be the top factors associated with productivity. Liberda et al. (2003) found lack of detailed planning, inadequate supervision, and lack of information to be the three factors that most significantly impacted productivity. Dai et al. (2009) implemented a nationwide survey involving nearly 2000 craft workers to examine the impacts of 83 different productivity factors. Factors involving tools and consumables, materials, engineering drawing management, and construction equipment were identified as having the greatest impact on productivity from the craft workers' perspective. Kimpland (2009) divided the top factors into two categories; internal and external. Lack of foreman planning and communication skills, cultural resistance to change, poor communication between foremen and project managers, and lack of technical training at the craft level were the top internal factors. Poor quality of plans and specifications, slow responses to questions, unrealistic schedule demands from the customer, and lack of qualified foremen and craft workers were the top external factors.

As discussed above, there have been decades of previous efforts in variation and classifying productivity factors. Figure 2.1 below illustrates many of the articles described above. Unlike this research, previous efforts have focused on one or the other (productivity or variation). Previous efforts have not addressed the root causes of variation in terms of how the factors affect construction task starting times and duration.

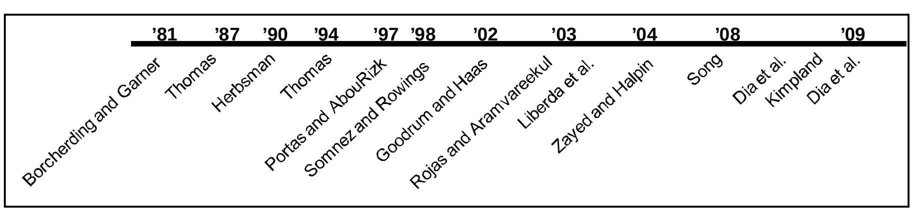


Figure 2.1: Chronology of Construction Labor Productivity Research

2.3 Research Pertaining to the Lean Construction Planning Philosophy

2.3.1 Lean Construction Background

The following background information on the Lean Construction Institute (LCI) was obtained from the organization's website: www.leanconstruction.org. LCI, a non-profit research organization, was founded by Glenn Ballard and Greg Howell in August 1997. LCI's purpose is to reform the management of production in design, engineering and construction for capital facilities. LCI developed the Lean Project Delivery System® (LPDS) that applies principles pioneered in manufacturing to construction. LPDS® tools facilitate planning and control, maximizing value and minimizing waste throughout the construction process. The key differences between lean construction and other forms of project management include:

- **Control** is redefined from "monitoring results" to "making things happen." Planning system performance is measured and improved to assure reliable workflow and predictable project outcomes.
- **Performance** is maximizing value and minimizing waste at the project level. It is claimed that current practice attempts to optimize each activity and thus reduces total performance.
- **Project Delivery** is the simultaneous design of the facility and its production process. This is concurrent engineering. Current practice, even with constructability reviews is a sequential process unable to prevent wasteful iterations.

- **Value** to the customer is defined, created and delivered throughout the life of the project. In current practice, the owner is expected to completely define requirements at the outset for delivery at the end, despite changing markets, technology and business practices.
- **Coordinating action through pulling and continuous flow** as opposed to traditional schedule driven push with its over-reliance on central authority and project schedules to manage resources and coordinate work.
- **Decentralizing** decision making through transparency and empowerment. This means providing project participants with information on the state of the production systems and empowering them to take action.

In summary, lean construction is a production management based project delivery system emphasizing the reliable and speedy delivery of value. It challenges the generally accepted belief that there is always a trade between time, cost and quality.

2.3.2 Lean Construction Planning

Planning is one of the key aspects of lean construction this research is focused on. The Last Planner System (LPS®) is the planning process associated with and advocated by the LCI. It involves collaborative planning / scheduling intended to engage all members of the project team. Figure 2.2 below illustrates the flow process associated with the LPS®.

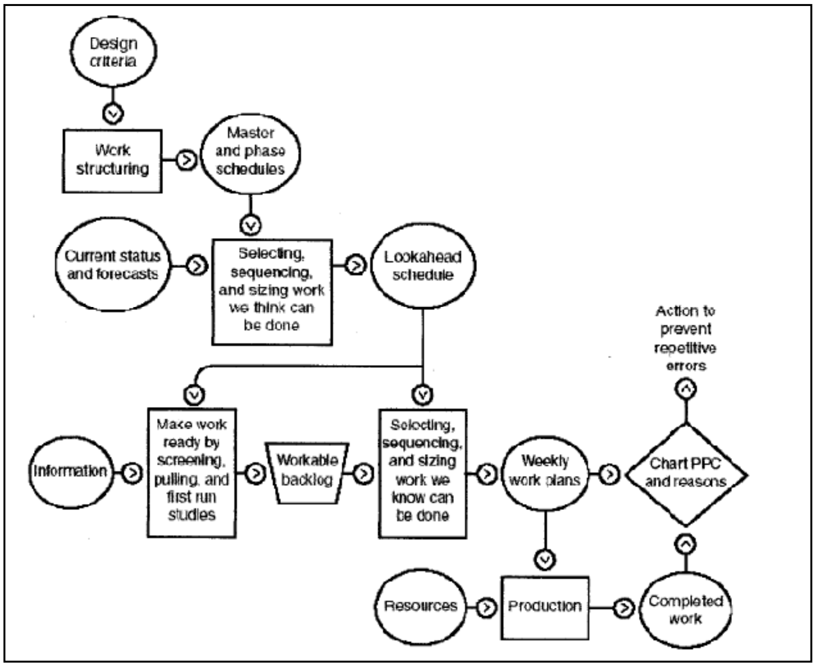


Figure 2.2: Last Planner System® of Production Control (Ballard 2003)

The primary purpose of collaborative planning is to ensure reliable weekly work plans are created. This is accomplished by identifying all of the tasks/conditions that must be accomplished to "make ready" the work that is being scheduled. It is essentially identifying all of the pre-requisite tasks for a given item and then ensuring it is feasible for those pre-requisites to be completed.

The Weekly Work Plan (WWP) meeting is where this collaborative planning occurs in order to create the WWP. The WWP is built around all of the team members making reliable promises. To be more specific, the last planners (i.e. often the trade foremen on site) only promise they will accomplish a task once it is clarified that the identified pre-requisite conditions will be satisfied. Figure 2.3 below shows an example of a WWP.

Weekly work plan

project

Stage

area

Week commencing

Company

Prepared by

Date prepared

ref	Task description	Final MakeReady needs		Period to perform the task							PPC analysis		
	Criteria for release of assignments: defined, sound, ordered, sized	Work that must and can be performed prior to the release of this task	who will do work	M	T	W	T	F	S	S	Y	N	Reasons for incomplete*

Figure 2.3: Example of a Portion of a Weekly Work Plan

Look-aheads are an important aspect of the LPS®. Alarcón et al. (2005) found that PPC improved when companies included the use of look-aheads while implementing the LPS®. One of the key purposes of the look-ahead is to identify and remove constraints, which are items that need to be completed or addressed prior to a task being started (Ballard 1997). Some categorical examples of constraints are the contract, design, materials, labor and equipment, and prerequisite work (Choo et al. 1999). Once the constraints for a task have been removed, the task is “made ready” and the commitment to accomplish the task is more reliable (González et al. 2010).

A key measure of success of the LPS® is the PPC. It measures the percentage of tasks from the weekly work plan that were completed. Ballard’s research was focused on PPC and he found that by using a collaborative planning approach like the LPS®, PPC typically increased from about 55% to over 70% (Ballard 2000). It has also been shown that construction labor productivity is positively correlated with PPC (Liu and Ballard 2009). One aspect that the PPC doesn’t capture is severity. One can determine the frequency in which a specific cause of variation occurs based on using the PPC, but it cannot be determined whether the task that was not completed simply required an additional hour to complete or if it caused a delay of a week or more. The use of the risk assessment matrix in this research addresses this limitation.

2.4 Construction Research Pertaining to the Use of Factor Analysis

2.4.1 Factor Analysis Background

Factor analysis has been thoroughly studied by several researchers, for example (Spearman, 1927; Harman, 1976; Kim and Mueller, 1978). Factor analysis is used when analyzing a number of individual items in which multicollinearity exists. Multicollinearity is a condition in which the independent variables are themselves correlated (Ott and Longnecker, 2001). Several individual causes of variation are considered during this research. It is hypothesized that multicollinearity exists, and some of those individual causes of variation are correlated to the others. Factor Analysis is based on the assumption the observed variables (i.e. those causing variation – for this research) can be explained by some underlying factors, which are smaller in number than the observed variables (Comrey and Lee, 1992).

2.4.2 Factor Analysis Use in Construction Research

Trost and Oberlender (2003) studied the prediction of early cost estimate accuracy for construction projects. They used factor analysis to group 45 elements related to predicting early cost estimates into 11 different factors. Those factors were used to develop a model for predicting estimate accuracy. Doloi (2007) performed factor analysis to identify major factors associated with motivational attributes affecting productivity in Australian construction industries. Factor analysis was used to group 35 critical success factors pertaining to the competitiveness of contractors into eight clusters (Lu et al., 2008). Dai et al. (2009) used factor analysis to analyze survey data collected pertaining to factors affecting productivity. They identified 10 latent factors to represent the underlying structure of 83 productivity factors. Although factor analysis is a common method to analyze data, no researchers have used it to analyze how the individual causes of variation of construction tasks are interrelated.

2.5 Construction Research Pertaining to the Use of Social Networks

2.5.1 Social Network Background

The concept of social network analysis (SNA) was first introduced in the 1930s and original studies focused on the social and political relationships between individuals (Moreno 1960). Barnes (1954) started using the term “social network” to denote patterns of ties, concepts usually used by social scientists: bounded groups (e.g., tribes, families) and social categories (e.g., gender, ethnicity). Graphs, or sociograms, were created with nodes representing individuals and the links between the nodes representing relationships between the individuals. In this context, sociograms were put forward as a fundamental tool for investigating the fabric of interpersonal relationships within groups of individuals (Chinowski et al. 2008).

2.5.2 Social Network Use in Construction Research

There has been limited research using social networks in the construction field. Thorpe and Meade (2001) used social networks to determine if project specific websites could be used to pull information and more effectively design & build complex projects. They surveyed members of the design and construction team to determine communications patterns; more specifically, with whom and how often did the different teams members communicate. Their SNA identified key members of the team in terms of communication and illustrated the challenges that can arise when one of those key members does not participate, or use the project specific website. Social networks have also been used in the development of a model for achieving high performance results from project teams. Chinowski et al. (2008) modeled the mechanics and the dynamics, the what and why respectively, of information passed between the team members. Much like Thorpe and Meade (2001), they surveyed team members and used SNA to determine a graphical representation of the communication architecture within the team. In their study, architects were in infrequent contact with the team during the majority of decision-making processes. They concluded that the isolation of key individuals contributed to over centralized decision making, a lack of information and knowledge integration, and a lack of trust (Chinowski et al. 2008). "In projects where trust and value sharing are not evident, the impact on information and knowledge sharing can be significant." SNA was also used in the construction industry to examine the mediating role played by individuals that share the same nationality as an international partner on a project (Di Marco et al. 2010). They studied the internal communications between two different project teams executing complex, reciprocally interdependent design projects in India. One team was comprised of Indians and Americans. The other team was identical, but also contained an Indian national who had studied and worked in the United States. Using SNA to represent the communication patterns, they found the Indian expatriate played a cultural boundary spanning role by resolving cross-cultural knowledge system conflicts and increased collaboration effectiveness (Di Marco et al. 2010).

2.6 Multi-Criteria Decision Making (MCDM) Techniques

2.6.1 MCDM Overview

"The theory of decision analysis is designed to help the individual make a choice among a set of prespecified alternatives" (Keeney and Raiffa, 1976). The MCDM techniques are intended to support decision makers with this process of determining which of the competing alternatives is preferred over the others while the alternatives may conflict with each other when evaluated against different criteria. The MCDM techniques enable the decision maker to rank and/or assign weights of importance to the criteria, compare the alternatives to each other in terms of the criteria, and determine the preferred alternative. There are several techniques including the analytical hierarchy process (AHP), multi-attribute utility theory (MAUT), and ELimination Et Choix Traduisant la REalité (ELECTRE). Numerous texts and extensive research have been dedicated to these methods of MCDM (Keeney and Raiffa, 1976; Edwards, 1977; Edwards and Barron, 1994; Roy, 1996; Belton and Stewart, 2002; Saaty, 1980, 1987, 2008).

Although each of these methods has the goal of determining which alternative is preferred, the AHP is a more plausible fit for this research due to two primary differences. The first is the ability to assign criteria weights and the other is transitivity. The AHP uses systematic pairwise comparisons to determine criteria weights. MAUT methods do not assign importance weights to the criteria. This is also a problem with ELECTRE because only qualitative criteria levels are required to construct the concordance and discordance indices (Vargas and Hsiang, 2010). Transitivity between preferences means that if alternative A is preferred to alternative B, and alternative B is preferred to alternative C, then alternative A is preferred to alternative C. Without the transitivity axiom, MAUT does not work. The AHP does not assume transitivity and, given an intransitive situation, the decision maker has available procedures for finding and mitigating it if deemed appropriate (Gass 1998). The AHP method was used in this research due to the differences mentioned above and because it has been tested, is theoretically sound, readily understood, and easily implemented (Forman and Gass, 2001).

2.6.2 Additional AHP Background and Benefits

The AHP is a performance aggregation tool that facilitates decision making when several aspects must be considered and some are favored over others for each of the available options. AHP considers both qualitative and quantitative information and combines them by decomposing ill-structured problems into systematic hierarchies to rank alternatives based on numerous criteria. There are several benefits of using AHP as a decision support system, including (Hsiang, 2010):

1. AHP estimates the weight for each criterion and the final weighted average score for each alternative.
2. AHP provides insights into the quantifiable elements of the process; thereby establish a better understanding of the final decision.
3. AHP provides simple and readable rules of evaluation for checking the consistency of the evaluation measures to integrate human subjectivity, experience, and knowledge into the decision process.
4. AHP comprises uncertainty, risk and fuzziness.
5. AHP supports group decision-making.
6. AHP supports a verifiable, effective means of dealing with complex situations.
7. AHP unifies treatment of qualitative and quantitative merits.

Figure 2.4 shows the AHP uses pairwise comparisons between quantitative or qualitative criteria to assess the relative importance of each criterion. These can be arranged in a hierarchical manner for sets of attributes, and qualities (levels) within these attributes. As such, the qualities of different attributes are not directly compared. Table 2.2 lists the four primary steps in using the AHP Model.

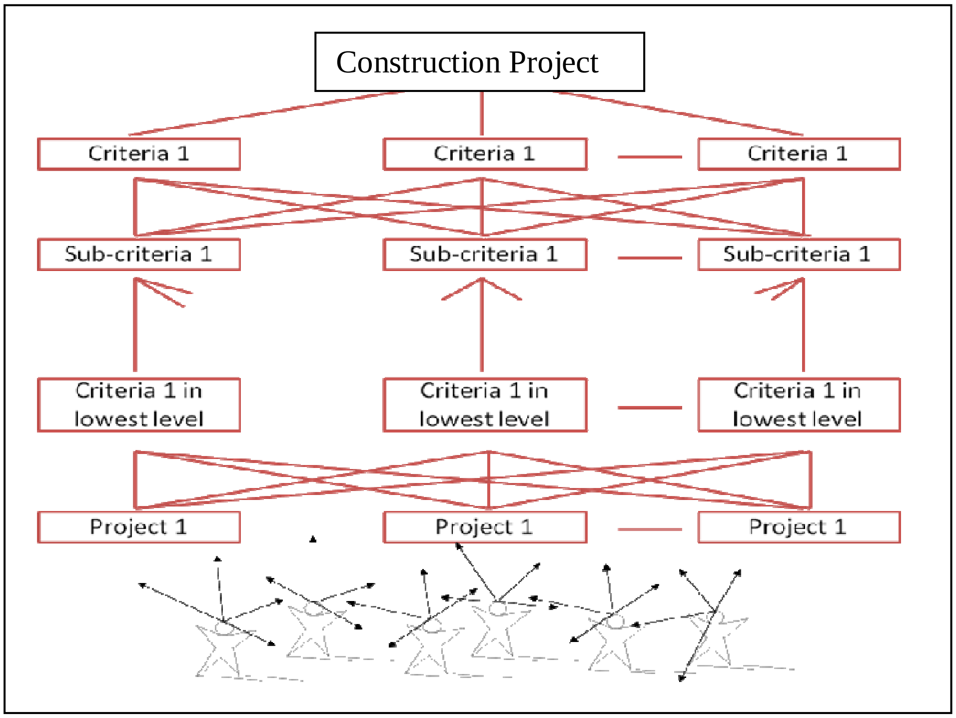


Figure 2.4: AHP Model Overview (Hsiang, 2010)

Table 2.2: Primary Steps in the AHP

Step	Description
1	Determine Selection Criteria Weights
2	Determine Score for each Alternative (Projects in Figure 2.4)
3	Determine Preferred Alternative
4	Calculated and check Consistency Ratio

2.6.3 AHP Use in Construction Research

AHP has been used as a decision making tool in several areas related to construction. Shapira and Simcha (2009) used AHP to determine the relative importance of safety factors pertaining to tower crane operations on a construction site. The factor weights will also be used in their development of a comprehensive model that will allow the computation of safety indices for individual construction sites employing tower cranes. Zhang and Zou (2007) used an AHP model for the appraisal of the risk environment pertaining to the joint ventures to support the rational decision making of project stakeholders. They concluded that the AHP model was effective in addressing the risks involved in joint venture projects. Goldenberg and Shapira (2007) developed an AHP-based model to address several qualitative categories such as managerial convenience, operational efficiency, progress delays, and work safety in the selection of critical construction equipment. Little, if any, research has been conducted while using the AHP as a means to assist with the determination of which trades should be focused on to reduce variation.

2.7 Summary

Considerable research has been performed over the years on factors affecting productivity. This research is used as the basis of studying variation of construction related tasks. As previously mentioned, there has also been extensive research associated with variation; however, the literature review has identified four primary gaps in the body of knowledge.

1. There is a need to identify the causes and quantities of variation that exist within a construction project.
2. No references were found to prioritize which causes of variation are posing the greatest risk to project performance.

3. No social network analysis research has been focused toward the trades within a project.
4. No decision support systems were identified that target and determine the feasibility of reducing variation for a construction project.

This research is important and valuable as it serves to address these gaps in the body of knowledge. Additionally, this research has a broader impact on the construction community. It provides the framework and repeatable analytical methods to identify, prioritize, and reduce variation on a construction project. The techniques and procedures used in this research can be applied to other construction projects as well.

CHAPTER 3

3.0 METHODOLOGY

For each data collection method, the survey and each case study, this chapter will highlight the primary research objectives that are supported. It will also provide an overview of the design method, the associated data collection plan, and the analysis techniques used for each of those methods.

3.1 Variation Survey

3.1.1 Research Objectives addressed by the Variation Survey

Objective 1: Determine the prevalent individual causes of variation and how workers, foremen, and project managers view the causes differently.

Objective 2: Identify underlying factors that correlate the individual causes of variation in terms of starting time and duration.

3.1.2 Variation Survey Overview and Design

The literature review identified 166 items that affect productivity. (Borcherding and Garner 1981; Thomas and Yiakoumis 1987; Herbsman and Ellis 1990; Thomas and Sakarcan 1994; Portas and AbouRizk 1997; Somnez and Rowings 1998; Goodrum and Haas 2002; Rojas and Aramvareekul 200; Liberda et al. 2003; Zayed and Halpin 2004; Song

2008; Dai et al. 2009; Kimpland 2009). These 166 items were cross referenced and reduced to 50 causes based on the following two procedures:

1) Causes that were only suitable for specific projects and tasks were removed. For example, Somnez and Rowings (1998) identified the concrete pump as a significant factor affecting productivity of placing concrete. Since concrete specialty contractors probably would only represent a portion of the surveyed companies, to avoid a very long survey and ensure good quality of the response, concrete pump was not listed as a separate factor in the survey. Instead, the pump would simply be considered "equipment."

2) Similar causes under the same category were combined. For example, hard hat, safety vest, and safety glasses were combined as personal protective equipment.

The 50 causes were then placed into one of eight main categories. Koskela (2000) used a similar framework when discussing categories that impact productivity. Koskela's seven categories were connected work (prerequisite work), detailed construction design, components and materials, workers, equipment and tools, space (jobsite), and external conditions. These same seven areas were used and one additional category, management / supervision / information flow, was added. The eight categories used in this study are listed below:

1) *Prerequisite Work:* Items that must be completed before a task can begin.

2) *Detailed Design / Working Method:* Having an accurate and available design or drawing and a feasible working method in order to accomplish a given task.

3) *Labor Force:* Labor force available and trained to perform the required task(s).

4) *Tools/Equipment:* Required tools or equipment available in sufficient quantities and conditions.

5) *Material and Components:* Having the correct and necessary materials available when and where needed.

6) *Work / Jobsite Conditions:* Adequate physical space available to perform the task.

7) *Management/Supervision/Information Flow:* Systems exist to develop the work plan or schedule, provide guidance or instruction, and to answer questions when they arise.

8) *Weather or External Factors:* Items that occur which are outside the control of those in your company.

Each category included a number of potential individual causes for variation. Table 3.1 lists the 50 individual causes and illustrates how they are distributed among the 8 categories.

Table 3.1: Individual Causes of Task Starting Time Variation

1. Prerequisite Work:
Obtaining required permits for the work to begin
Completion of previous work (i.e. work before you isn't done yet)
Rework being required due to the quality of previous work
Poor quality of previous work (though not to a level that requires rework)
Inspections for previously completed work
2. Detailed design and work method:
Design constructability
Quality of documents (errors in design and/or drawings)
Turnaround time from engineers when there is a question with a drawing
Strict specification requirements
Quality control requirements
Work complexity
Work sequence or method is not well planned
Low degree of repetition (task constantly changing)
Inadequate instruction on detailed working method

Table 3.1 Continued

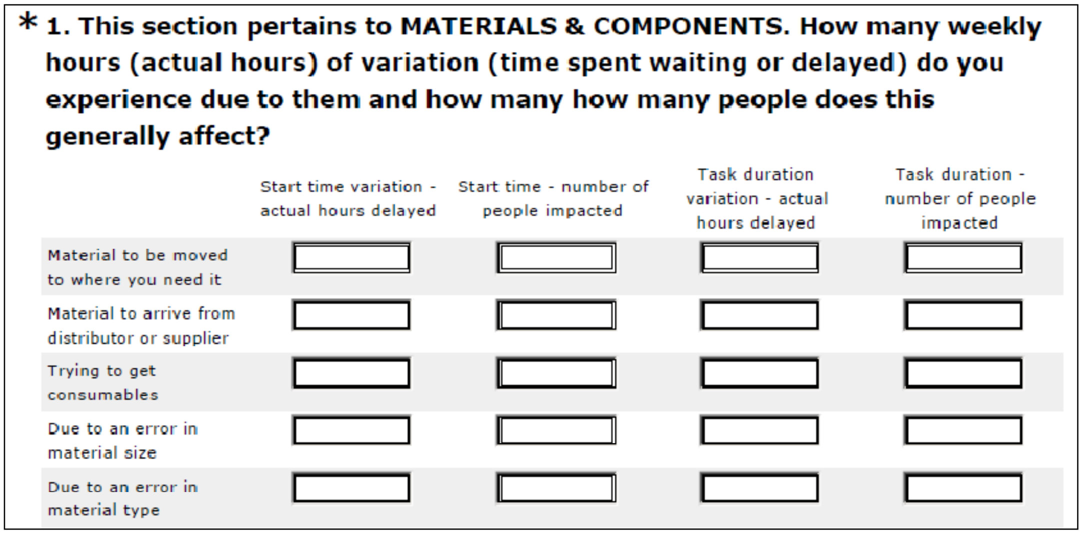
3. Labor Force:
Socializing (talking with fellow workers)
Absenteeism
People arriving late and/or leaving early due to illness, injury, family or personal reason, etc.)
Low morale and/or lack of motivation
Getting moved to another job/task before the one you were working on was completed
Crew size is inadequate
Inefficiencies associated with personnel turnover (i.e. new employees)
Experience on similar tasks (i.e. there is a learning curve associated with non-repetitive tasks)
Worker/crew lack of skills/experience to perform the task(s) being asked of them
Language barrier among workers and/or worker-supervisor
4. Tools and Equipment:
Personnel Lift (unavailable, no operator, not the priority, maintenance)
Power Tools (not trained, used by someone else, misplaced, maintenance)
Crane or Forklift (unavailable, no operator, not the priority, maintenance)
Hand Tools (used by someone else, misplaced, maintenance)
Other heavy equipment (backhoe, loader, dump truck, etc.) not available
Personal Protective Equipment (PPE) [not enough, used by someone else, misplaced, unserviceable]
5. Materials and Components:
Material needs to be moved to where you need it
Material to arrive from distributor or supplier
Trying to get consumables
Error In material size
Error In material type
6. Work / Job Site:
Overcrowded work area / jobsite congestion
Difficult access to work area
Site Layout - distance between material storage and where material is required for work is excessive
7. Management / Supervision / Information Flow:
Wait to get answers to questions you have about the design or drawing
Need guidance or instruction from supervisor
Lack of field manager (foreman) skill/knowledge
Coordination between different trades
Over commitment due to a tight work schedule
Foreman availability
Change in scope of work
Foreman communication skills
Communication between:
Owner/Engineer and project manager
Project manager and foreman
Foreman and workers
8. Weather / External Conditions:
Weather impacts (excessive heat, cold, wind, rain, etc.)

3.1.3 Variation Survey Data Collection Plan

A questionnaire survey was developed to address the first research objective by identifying the most prevalent causes of starting time and task duration variation during a typical week of work. It involved craft workers, foremen, and project managers and consisted of two parts. In this research, craft workers are also referred to as laborers and include both skilled and unskilled workers.

In the first part of the survey, respondents provided background information such as their trade, position, size of their company, whether they work for a union or not, and their level of experience. The second part of the survey involved collecting feedback pertaining to variation of the causes previously described for this research. Respondents were asked to rank order the eight overall categories and indicated how many weekly hours of variation, in terms of task starting times and duration, they experienced due to each of the 50 causes listed in Table 3.1.

An example of a typical question is provided below in Figure 3.1 and the entire survey can be found in Appendix A. This example pertains to the materials and components category. There were five causes of variation, listed on the left side of the figure, for the respondents to consider. The respondents indicated how many hours of variation they experienced and how many people were impacted during a typical week for each of the five causes. The first two columns pertained to starting time variation and the second two columns pertained to task duration variation.



* 1. This section pertains to MATERIALS & COMPONENTS. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect?

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
Material to be moved to where you need it				
Material to arrive from distributor or supplier				
Trying to get consumables				
Due to an error in material size				
Due to an error in material type				

Figure 3.1: Survey Question Pertaining to Individual Causes of Variation

3.1.4 Variation Survey Data Calibration

Careful attention was given to several potential problem areas regarding errors associated with surveys. To mitigate measurement errors due to language barriers, the survey was translated to Spanish as many people in the construction industry speak Spanish as their primary language. A pilot study was conducted with a local construction company to reduce potential measurement errors due to weaknesses in the wording of questions and/or the lack of requisite instruction for respondents to answer the questions. The survey was distributed to the general contractor’s project manager, three foremen (electrical, mechanical, and roofing trades), and 10 laborers (three electrical, four mechanical, and three roofing). Each person was asked to read the directions and then complete the survey, which took approximately 25 minutes. The purpose was to determine if the respondents were able to complete the survey without any external guidance, and to see if there were any causes of variation they felt were missing.

The members of the pilot study felt an example of starting time and task duration variation should be added to the instructions to better explain each of them. They also felt "socializing" was a cause of variation that should be added to the survey. Both of these items were addressed prior to the distribution of the survey. Both the online version and the paper version utilized the same format to minimize errors due to the mode of data collection. The survey was distributed throughout the United States to minimize problems with coverage areas.

3.1.5 Variation Survey Distribution

The survey was distributed with the assistance of 22 US Army Corps of Engineer district offices, located throughout United States (Figure 3.2). These districts oversee all construction performed for the Corps of Engineers, thus they are in contact with a large number of construction contractors. These are civilian contractors performing public work under a government contract. Thirty-six district offices were contacted in the summer of 2009 and 22 agreed to assist with distributing the survey to their contractors. Additionally, a local construction consulting company distributed the survey to their client base throughout the United States.

Overall, approximately 260 companies received the survey. The project manager(s), foremen, and workers from the companies had the option to volunteer to take the survey. It is unknown how many project managers, foremen, and laborers were given the option to take the survey. The project managers, foremen, and laborers were chosen as the intended audience because their feedback was required to address the research objectives. Respondents had the option of taking the survey online or by hand. About five weeks (23 July – 30 August 2009) were allotted for the survey to be distributed, taken, and returned.

Figure 3.2: Locations of US Army Corps of Engineer Districts

3.1.6 Variation Survey Analysis Techniques

Factor analysis was used to help identify the underlying factors correlated with the individual causes of variation. Additionally, a concept map was developed based on the factor analysis results. The concept map was based on the number of trades involved with a project and can be use to prioritize planning efforts to prevent likely causes of variation from occurring.

3.2 Case Studies

The case studies were conducted to further validate the survey results and to gather quantitative data pertaining to actual construction projects. The initial intent was to perform a single study involving two companies that performed essentially the same type of work, with the primary difference being that one used lean and the other used traditional principles when it came to developing their weekly work plans. An associate of a local construction consulting company assisted with identifying potential candidates for the case study. Both of the companies perform masonry restoration work. One of them adopted the use of the LPS® during the summer of 2009 and is using lean principles in all aspects of their business, while the other is not. Both companies were initially contacted by the consulting associate and both expressed a desire to participate in the study. A proposal, which outlined the purpose, objectives, and type of data that would be collected, was developed and sent to each company. An example of the proposal can be found in Appendix B.

Due to concerns about relying on one case study and the desire to provide more breadth to the research, two other case studies were also incorporated into the research design. The LCI has several chapters located throughout the United States. One purpose of the chapters is to provide local lean support to owners, architects and designers, engineers, contractors, and suppliers. The establishment of the Carolinas Chapter of LCI helped identify two other local companies to participate in the case study. One of the companies was a general contractor and the other was a mechanical subcontractor. There was a separate study associated with each of the companies. As the research progressed, these two companies became the primary providers of quantitative data. One of the original masonry restoration companies never provided any data, therefore was not an integral part of the research. Despite this, a description of the planned study is included in this chapter and a discussion of what occurred is included in Chapters 4 and 5. Figure 3.3 depicts how the companies provide greater diversity in terms of the coupling of trade and project complexity. It is not the intent to imply that masonry restoration is not difficult; however, the masonry restoration projects were less complex than the other two projects in this research.

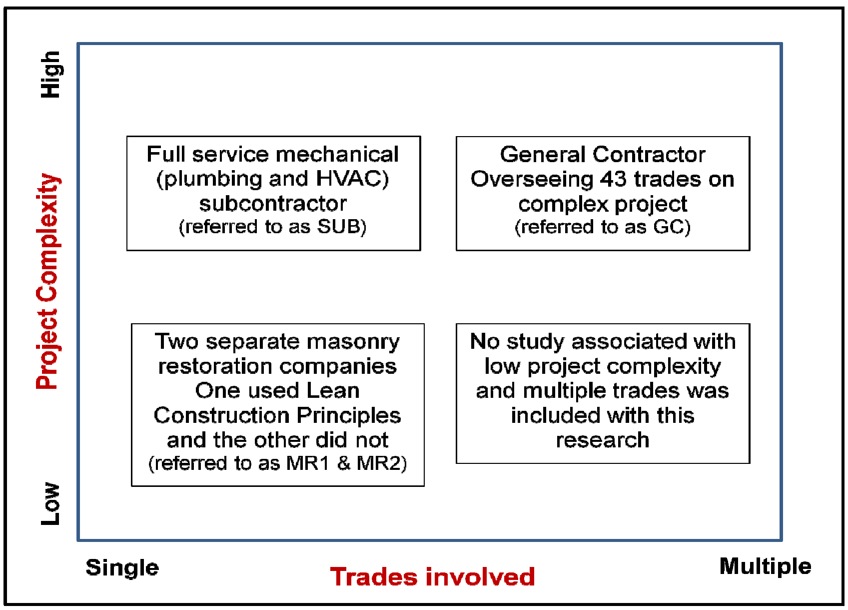


Figure 3.3: Coupling of Trade Involvement and Project Complexity for Case Studies

The following sections will explain each of the three case studies in further detail, to include the associated research objectives, an overview of the case study design, and the data collection plan.

3.3 Case Study 1 (General Contractor)

3.3.1 Research Objectives addressed by Case Study 1

Objective 3: Determine the causes of variation with the greatest risk of impacting project performance.

Objective 4: Develop the organizational social network of trades that exists among a construction project.

Objective 5: Analyze the social network to identify the key trades within the network.

Objective 6: Identify the organizational structure of contractors or trades associated with the variation posing the greatest risk to project performance.

Objective 7: Develop a decision support system to target trades in an effort to reduce variation.

3.3.2 Case Study 1 Overview and Design

A general contractor (GC) overseeing 43 subcontractors, also referred to as trades, involved with the construction of a single level, $50 million, 150,000 square foot data center was the primary participant of this case study. A GC with multiple subcontractors was chosen for the study because the research is partially focused on the social network that exists among the various trades. The project entailed the build-out of an existing warehouse building into a data center and white-space computer labs. The scope included the construction of a new steel structure within the building, new mechanical and electrical systems, raised access floor computer labs with associated support spaces, and a general office component. Construction ran from February through September 2010 and the project was studied from the beginning of March through completion at the end of September. The first three weeks of the project were not included in the study due to the limited scope and number of trades involved during that period. The GC held a weekly subcontractor meeting in which the foreman from each trade working on the site attended. The focus of the meeting was to identify and resolve conflicts (i.e. more than one trade working in the same area at the same time) by using a work breakdown structure. They also discussed material procurement for timely support of construction activities. Additionally, daily huddles were conducted to review the key tasks to be completed for the day. Table 3.2 summarizes both planning meetings.

Table 3.2: GC Planning Meetings for Case Study 1

	Weekly Meeting	Daily Huddle
Meeting Attendees	Project manager, superintendent, foreman from each trade working on the project	Project manager, superintendent, foreman from each trade working on the project
Meeting Duration	1-2 hours	15-30 minutes
Basic Agenda	1) Reviewed previous weeks' work and recorded: • Whether or not each task was completed • Reason for variation 2) Conducted 3 week look-ahead using master schedule 3) Developed weekly work plan for upcoming week in conjunction with the 3 week look-ahead: • Identified/resolved WBS conflicts • Focused on material procurement to support construction activities	Reviewed daily tasks • Address any concerns/questions

3.3.3 Case Study 1 Data Collection Plan

A total of 28 weeks' worth of data was collected for the project. The information collected included the planned and actual starting times and duration for each task on the work plan, as well as reasons for variation. Variation was tracked in terms of starting time and task duration. The starting time variation is the time difference between the planned and actual task starting time and the duration variation is the time difference between the planned and actual task duration.

3.3.4 Case Study 1 Analysis Techniques

Several analytical techniques were used in this case study. First, a risk assessment matrix was used to determine the causes of variation that posed the greatest risk to project performance. Social network analysis was performed using Pajek® to identify the social networks of trades. Both degree and eigenvector based centrality analysis was performed to ID the key trades within the social networks. Lastly, the analytical hierarchy process was used to support decision making when multiple criteria were involved with the decision.

3.4 Case Study 2 (Mechanical Subcontractor)

3.4.1 Research Objectives addressed by Case Study 2

Objective 3: Determine the causes of variation that pose the greatest risk of impacting project performance, in terms of productivity and cost.

Objective 8: Compare performance in terms of productivity and cost savings for two similar projects, in which the LPS® was used on one, but not the other.

3.4.2 Case Study 2 Overview and Design

A mechanical contractor specializing in plumbing, heating, ventilation, and air conditioning participated in this case study. The mechanical contractor was chosen for the study as mechanical related tasks are very common within the construction industry. The company was also chosen because they were interested in determining if using the LPS® would be effective, in terms of reducing variation and increasing productivity. For this research, a reference to the company's traditional planning system refers to not using the LPS®. The company compared the performance of two separate, but similar projects for the case study (Table 3.3).

The LPS® project was labeled as a renovation, but the renovation involved only modifying a portion of an existing building. Most of the work involved adding on a new structure adjacent to the existing one. There is also a difference between the number of cooling units as the LPS® project had 28, while the non-LPS® project only had 14. The work involved in the study was self-performed by the mechanical contractor using labor crews with similar experience and skill levels; however, there could still have been some differences due to learning curve issues. The projects also had the same project manager and superintendent for the first eight weeks of the study. The intent was to keep constant as many aspects as possible, so the differences in performance could be attributed to the differences in the planning processes of the projects. The costs, durations, and scopes of the primary mechanical aspects of the two projects are shown in Table 3.3. A general contractor and other trades were also working on both of these projects; however, they did not participate in this study. The focus of this study was on the mechanical contractor.

Table 3.3: Case Study 2 Project Costs, Durations, and Scopes

	LPS Project	Non-LPS Project
Project cost	$5.2 M	$2.9 M
Duration	16 months (Dec ’09 – Mar ’11)	12 months (Oct ’09 – Sep ’10)
Description and key aspects of overall mechanical scope	Renovation of existing building	New building
	28 cooling units	14 cooling units
	3 chillers	2 chillers
	2 cooling towers	2 cooling towers
	2 rooftop AC units	2 rooftop AC units

3.4.3 Case Study 2 Data Collection Plan

A total of 16 weeks’ worth of data was collected for each project. Since the projects were managed differently, in terms of planning, the data collected was slightly different. Table 3.4 outlines the participants and agenda for the planning meetings of each project.

Table 3.4: Case Study 2 Project Planning Meetings

	LPS Project	Non-LPS Project
Work Plan Meeting Attendees	Project manager, superintendent, foreman	Project manager, superintendent, foreman
Meeting frequency	Weekly	Biweekly
Meeting duration	45 minutes – 1 hour	30 – 45 minutes
Basic Agenda	Reviewed previous work – recorded: • Whether or not each task was completed • Quantity of variation • Reason for variation	Reviewed previous work (didn't record any information, simply adjusted upcoming schedule accordingly)
	Conducted 3 week look-ahead	Conducted 3 week look-ahead
	Developed weekly work plan for upcoming week in conjunction with the 3 week look-ahead: • Identified/addressed constraints • Considered previous/anticipated causes of variation	Developed weekly work plan by considering what needed to be done based on master schedule and whatever didn't get completed the following week

The project manager, superintendent, and foreman were involved with the planning meetings for both projects. The project that used the LPS® met weekly, where the non-LPS® project met bi-weekly. Aside from the frequency, the primary difference was in how the weekly work plans were developed. The LPS® project used the LPS® method (Ballard, 2000) as the basis for their weekly meetings. They reviewed the previous weeks' work plan and identified whether or not each task was completed. They also recorded the quantity and reason for any variation (i.e. the difference between what was planned and what actually happened) of each task on the weekly work plan. For example, if 100 labor hours were planned for a task and there were actually 120 labor hours spent on that task during the week, the quantity of variation would be 20 labor hours.

Both projects used a look-ahead process, but they were only similar in name. Look-aheads are typically used to give early warning of tasks scheduled to be started or completed in the look-ahead period. The team from the LPS® project conducted a 3 week look-ahead to consider activities on the master schedule and those that were not previously completed as candidates for inclusion on the upcoming weekly work plans. The LPS® project team in this research viewed constraints as potential causes of variation and used the "few trades" side of Figure 2 and previous experiences of the planning team to identify constraints. The LPS® project team also used the risk assessment matrix to determine which constraints, or causes of variation, were the most critical to remove. The non-LPS® project also conducted a 3 week look-ahead; however, they did not track any information pertaining to variation, nor did they perform a constraint analysis. They simply adjusted the upcoming schedule during the 3 week look-ahead to include any tasks that were not previously completed.

3.4.4 Case Study 2 Analysis Techniques

As with the first case study, a risk assessment was performed to identify and prioritize variation for reduction. This study also used a benefit / cost analysis to determine whether it was desirable to use the LPS® system to reduce variation and improve labor productivity.

3.5 Case Study 3 (Masonry Restoration Companies)

This case study was intended to examine differences in the project performance of two companies executing similar projects while using different planning philosophies; however, one of the companies did not provide any data pertaining to their project. Therefore, the results of this study are limited by the information and observations I obtained during a single site visit to that company's project site.

3.5.1 Research Objectives addressed by Case Study 3

Objective 3: Determine the causes of variation that pose the greatest risk of impacting project performance, in terms of productivity and cost.

Objective 8: Compare performance in terms of productivity and cost savings for two similar projects, in which the LPS™ was used on one, but not the other.

3.5.2 Case Study 3 Overview and Design

This study was intended to follow along the same lines as Case Study 2, except instead of one company internally comparing two similar projects; the performance of two separate companies performing similar projects were going to be compared. These two companies were initially identified by the local construction consulting company that assisted with distribution of the variation survey. Both of the companies performed masonry restoration work. One of the companies (referred to as MR1), used the LPS® and the other, referred to as MR2, did not. MR1 consists of approximately 40 employees and performs masonry restoration work throughout the eastern portion of the United States and has been using the LPS®, as well as other Lean Construction practices, since the summer of 2009. MR2 also specializes in masonry restoration work and has approximately 40 branch offices located throughout the United States. Each branch is about the size of MR1; therefore, the work from one MR2 branch was going to be used in the case study.

Since MR1 is a smaller company and does fewer projects during the course of a year, the scope of the projects for the study was based upon MR1's scheduled projects. After MR1 identified a project for the study, MR2 used it as a baseline to identify a project similar in scope. The masonry restoration projects for both MR1 and MR2 were in urban areas in the eastern/northeastern part of the United States. The project for MR1 involved the exterior of an 11 story apartment complex that remained in use by the tenants. The project for MR2 involved a 16 story office building that also remained in use during construction activities. The specific details for the MR2 project were not provided; however, the branch manager from MR2 said their project was similar to that MR1's project, for which the scope, duration, cost, and description of tasks are outlined in Table 3.5.

Table 3.5: Scope, Duration, Cost and Tasks for MR1's Project

Scope:	Repoint brick - 2400 linear feet		**General Steps involved with work**	
	Brick replacement - 600 units		Set up swing	
	Brick patching - 1700 units		Construct ground protection	
	Wash exterior elevations		Wash building	
	Waterproof exterior elevations		Inspect	
			Demo	
				Cut old pointing
				Prep patches (cut/remove bad portion of brick)
Duration:	12 weeks (April - June 2010)			Remove entire brick(s)
				Remove any caulk to be replaced
			Repair	
				Replace brick(s)
Cost:	$145k			Patch brick(s)
				Repoint
			Masonry wash	
			Replace caulk	
			Waterproof	

3.5.3 Case Study 3 Data Collection Plan

The data collection plan was intended to capture four primary aspects related to each project. Figure 3.4 is a template that was provided to each company to assist with the data collection. The first aspect had to do with who was involved with developing the weekly work plan and how long they spent doing it. The remainder of the template pertained to the project's weekly performance. The tasks were to be listed, along with their planned and actual starting times and durations. Columns were also included to indicate whether or not the task was completed, the amount of variation associated with the task, as well as the reason for the variation if it occurred. The bottom portion of the template tracked the weekly PPC and labor productivity.

Weekly Case Study Tracker (NCSU & Company Name):

Work Week: ________ to ________ of ____________________ 2010

Project:________________________

Planning: for weekly work plan below	Attendees ($ rate/hr)			
	PM	Supplier	Duration:	
	Foreman	Owner	Cost:	
	GC	A/E		
	Sub	Sub		
	Sub	Sub		

Date:

Weekly performance (as result of planning effort above):

Weekly work plan			Starting Time				Task Duration			
Date:	Task:	Completed Y/N	Planned	Actual	Hours of Variation	* Reason Code	Planned	Actual	Hours of Variation	* Reason Code

Percent Planned Compete (PPC): Number tasks completed from weekly work plan: ________

Number tasks on weekly work plan: ________

PPC = (Number complete / Number planned) x 100 =

Weekly Productivity

(Output / Labor hours of input): ________

Figure 3.4: Data Collection Template for MR1 and MR2

3.5.4 Case Study 3 Analysis Techniques

The analysis techniques that were planned for use in this case study were consistent with the other two case studies. A risk assessment matrix was going to be used to identify which causes of variation posed the greatest impact to the project based on frequency and severity. The hypothesis was that although the planning costs would be higher for the LPS® project, the associated productivity and PPC would be higher and the variation would be lower. The AHP would have used planning costs, productivity, PPC, and variation as the criteria. The performance of the projects was going to be used to score each in terms of those criteria.

CHAPTER 4

4.0 RESEARCH EXECUTION / RESULTS

4.1 Variation Survey

4.1.1 Variation Survey Results

A total of 124 useable responses were obtained. There were 108 responses that were not used in the analysis because they were either incomplete or they contained extreme outliers. Only the first one to three questions were answered in case of the incomplete surveys. If a respondent claimed the weekly average hourly variation was 25-30 hours in almost every category, while the average of the other responses was in the area of 1-2 hours, the former were considered extreme outliers. Project managers made up 64% of the responses, followed by laborers with 20% and foremen with 14%. The remaining 2% of the respondents did not identify their position. Contractors working for the US Army Corps of Engineers accounted for 80% of the responses, while the other 20% were from clients of the local construction consulting company.

Subcontractors and general contractors respectively provided 62% and 32% of the responses, with the remaining 6% unspecified. Twenty nine percent of the respondents were associated with four or more trades (electrical, mechanical, concrete, steel, etc.). Twenty six percent were associated with concrete, 19% with piping or plumbing, 11% with earthwork, and 8% with mechanical and HVAC. The remaining 7% was split among electrical, steel, roofing, drywall, or unspecified trades. Figure 4.1, Figure 4.2, and Figure 4.3 graphically depict the demographics of the survey respondents.

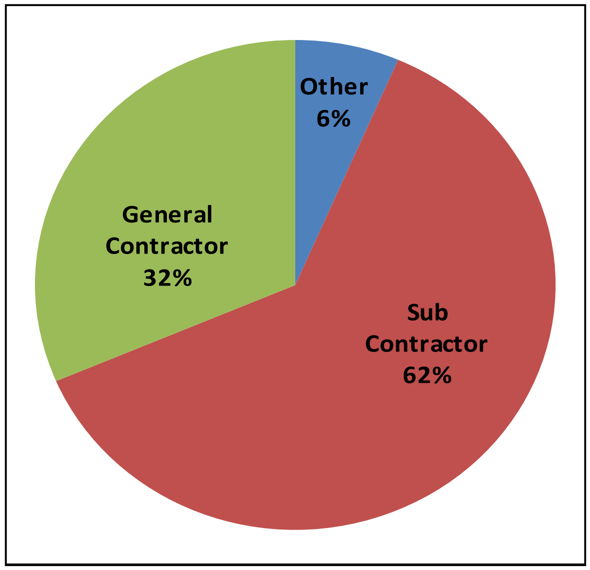


Figure 4.1: Company Types for Variation Survey

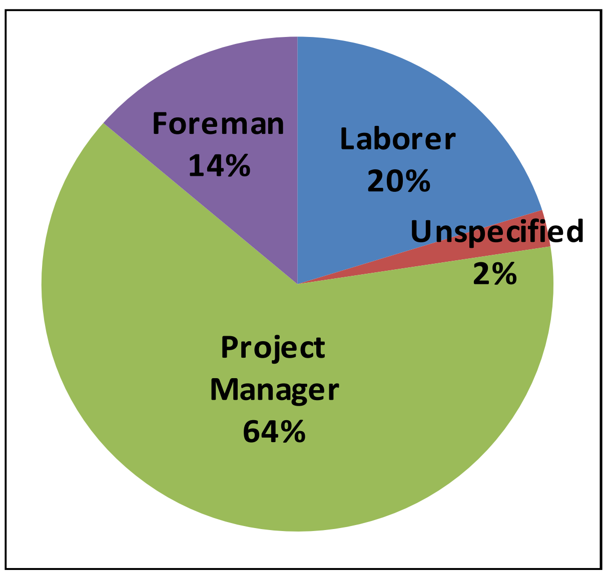


Figure 4.2: Position Distribution for Variation Survey

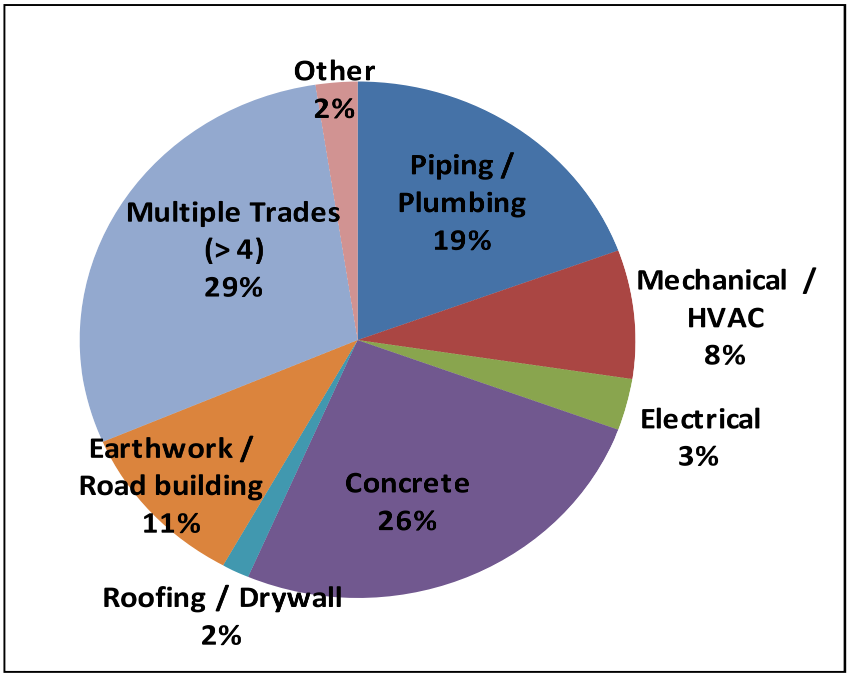


Figure 4.3: Trade Distribution for Variation Survey

4.1.2 Variation Survey Analysis

In order to determine the most prevalent factors causing starting time variation, the 50 causes were rank ordered three times (once by each of the three duty positions – laborer, foreman, and project manager) based upon the amount (hours / week) of variation they caused. These rankings were then consolidated, capturing the top five causes (i.e. the top 10%) according to each duty position, to identify the top overall causes of variation. The category (i.e. which one of the eight from Table 3.1) is also listed to illustrate which category the cause of variation is associated with. Table 4.1 contains the top eight causes of starting time variation. Table 4.1 was limited to the top eight causes since those eight captured the top 10% (i.e. the top 5) causes for the project managers, foremen, and laborers.

Although ordered slightly different, the top three causes in the view of laborers, foremen, and project managers was the same. It should be noted that the first and third cause are essentially the same; the question pertaining to turnaround time was included in two areas of the survey. It should also be noted that turnaround times for getting questions answered may be related to when the question is asked. Although the scope of the survey did not address this, it is likely a function of the lead time provided to engineering.

The top three causes are generally consistent with previous research. Borcherding and Garner (1981) found "rework" to be one of the top three factors affecting productivity. Kimpland (2009) found "slow responses to questions" to be one of the top two external factors that impacted productivity. Dai et al. (2009) found errors in drawings and the associated slow response time to questions to be among the top three items impacting productivity.

The remaining results indicate there are differences in the perceptions between the laborers and the foremen and project managers, particularly for causes No. 7 (people arriving late/leaving early) and No. 8 (needing guidance or instruction from their supervisor). The laborers state cause No. 7 (people arriving late and/or leaving early) is the 5th highest cause of starting time variation; however, the foremen and project managers don't have the same perception as foremen rank that cause 11th overall and the project managers rank it 16th. The laborers state cause No. 8 (needing guidance or instruction from their supervisor) is the 4th highest cause of starting time variation. The foremen and project managers perspective is different as they rank this cause 10th and 20th respectively. There is not a significant difference between the perceptions of the foremen and project managers with regard to starting time duration as all of their top five causes are ranked within the overall top six causes.

Table 4.1: Top Eight Causes of Starting Time Variation

No.	Cause	Category	Laborer Responses		Foremen Responses		Project Manager Responses	
			Hrs/Wk	Rank	Hrs/Wk	Rank	Hrs/Wk	Rank
1	Turnaround time from engineers when there is a question with a drawing	7 Supervsn/ Mgmt/Info	1.04	2	1.65	2	2.97	1
2	Completion of previous work (i.e. work before you isn't done yet)	1 Prerequisite Work	1.44	1	1.62	3	2.64	2
3	Wait to get answers to questions you have about the design or drawing	7 Supervsn/ Mgmt/Info	1.00	3	1.79	1	1.95	3
4	Obtaining required permits for the work to begin	1 Prerequisite Work	0.50	7	1.29	5	1.35	5
5	Quality of documents (errors in design and/or drawings)	1 Prerequisite Work	0.54	6	1.00	9	1.48	4
6	Rework being required due to the quality of previous work	1 Prerequisite Work	0.44	9	1.29	4	1.31	6
7	People arriving late and/or leaving early due to illness, injury, family or personal reason, etc.	3 Labor Force	0.58	5	0.97	11	0.93	16
8	Need guidance or instruction from supervisor	7 Supervsn/ Mgmt/Info	0.70	4	0.97	10	0.90	20

A similar approach was used with examining the variation of task duration. The nine most prevalent causes are shown in Table 4.2. There are nine causes in Table 4.2, versus only eight in Table 4.1, because it took nine causes to capture the top 10% of the causes of task duration variation for the project managers, foremen, and laborers. There was more discrepancy in perspectives when examining the task duration variation than there was with the starting time variation. The laborers stated, as they did with starting time variation, that needing guidance from their supervisor (cause No. 9) and people arriving late and/or leaving early (cause No. 8) are the 4^{th} and 5^{th} highest causes of task duration variation. Once again, the foremen and project managers did not have the same perception as foremen ranked those two causes 12^{th} and 15^{th} respectively. Project managers' perspectives differed by an even greater amount as they ranked those two causes 26^{th} and 19^{th} respectively. There is another difference in perception to illustrate when considering overall cause No. 6 - rework. Rework was in the top five causes for both the foremen and project managers, but is ranked 15^{th} in the view of the laborers. The only indication of a significant difference in perspective between the foremen and the project managers is with respect to the overall cause No. 7 - worker/crew skill level. The project managers rank this as the 4^{th} most important cause affecting task duration variation. The laborers have it as 9^{th} (still in their top ten), but foremen rank this as their 17^{th} cause.

Table 4.2: Top Nine Causes of Task Duration Variation

No.	Cause	Category	Laborer Responses		Foremen Responses		Project Manager Responses	
			Hrs/Wk	Rank	Hrs/Wk	Rank	Hrs/Wk	Rank
1	Wait to get answers to questions you have about the design or drawing	7 Supervsn/ Mgmt/Info	0.74	1	1.68	1	1.96	1
2	Turnaround time from engineers when there is a question with a drawing	7 Supervsn/ Mgmt/Info	0.54	2	1.24	3	1.93	2
3	Completion of previous work (i.e. work before you isn't done yet)	1 Prerequisite Work	0.40	7	1.29	2	1.81	3
4	Socializing (talking with fellow workers)	3 Labor Force	0.54	3	1.15	8	1.42	6
5	Weather impacts (excessive heat, cold, wind, rain, etc.)	8 Weather/ External	0.50	6	1.18	5	1.23	11
6	Rework being required due to the quality of previous work	1 Prerequisite Work	0.24	15	1.24	4	1.49	5
7	Worker/crew lack of skills/experience to perform the task(s) being asked of them	3 Labor Force	0.32	9	0.76	17	1.58	4
8	People arriving late and/or leaving early due to illness, injury, family or personal reason, etc.	3 Labor Force	0.52	5	0.76	15	0.93	19
9	Need guidance or instruction from supervisor	7 Supervsn/ Mgmt/Info	0.52	4	0.88	12	0.81	26

Unlike previous research, this research also examined the overall magnitude of the variation in terms of hours per week. The results indicated there was a perception of a larger amount of variation with an increase in management level. Consider the first cause of variation listed in Table 4.2. The perception of variation increases from 0.74 Hrs/wk for laborers, to 1.68 Hrs/wk for foremen, to 1.96 Hrs/wk for project managers. A possible explanation is that the span of responsibility increases as you move from laborer to foremen to project manager, therefore the perceived amount of variation increases. Laborers are typically only concerned with the specific task they are working on, while a foreman may have several tasks he is responsible for; thus, the foreman perceives a greater amount of variation due to the increased span of responsibility or concern.

The overall magnitude of variation was also examined for the prevalent causes identified in Table 4.1and Table 4.2 to determine how much of a typical 40-hour work week is impacted by variation. The weekly hours of variation were summed for the laborers, foremen, and project managers in terms of both starting time and task duration variation. For example, the sum of the top eight causes of starting time variation from a laborers perspective is 1.04 + 1.44 + … + 0.70 = 6.2 Hrs/wk. The same method was used for the foremen and project managers. The starting time and task duration variation were assumed to be independent in the survey, therefore they are added together to get the total weekly variation for each of the respondent categories. An average of their responses indicates an average of 19.3 hours of variation exist per week as shown in Table 4.3. Assuming a 40 hour work week, a total variation of 19.3 hours implies that a schedule is only about 52% accurate. This is consistent with results reported by Ballard (2000) pertaining to PPC, who found the average weekly PPC was 54% in over 450 weeks' worth of project data.

One obvious observation of the survey data is that both the size and complexity of projects increase as one moves up the duty position. As such, there is a need to find plausible managerial organizations to reduce the complexity, to factorize the causes of variations, or at least keep them from growing proportionally with the project size.

Table 4.3: Total Average Weekly Variation

Variation Category	Laborer	Foremen	Project Manager
Starting Time Variation	6.2	10.6	13.5
Task Duration Variation	4.3	10.2	13.2
Total Variation	10.5	20.8	26.7
Average Variation (hrs/wk)	**19.3**		

Research Objective 2: Identify underlying factors that correlate the individual causes of variation in terms of starting time and duration.

The initial analysis performed identified the top individual causes of variation based on the magnitude of the cause and the combined input of laborers, foremen, and project managers. One of the aspects of the construction process which makes it complicated is the multitude of activities that are interconnected. There are often numerous prerequisite tasks that must be completed prior to a new task starting. For example, before concrete can be placed, the formwork must be erected and the reinforcement needs to be placed, tied, and inspected. The variation of one of these tasks can affect the other tasks. There is likely to be considerable multicollinearity among the causes of variation. Multicollinearity is a condition wherein one or more of the independent variables can be approximated by a linear combination of the other independent variables (Trost, 2003).

Factor analysis is a statistical technique that can be used to identify a relatively small number of factors to represent relationships among many interrelated variables (Paul, 1994). This is one goal of factor analysis - to represent the covariance structure of multivariate data by a few underlying but unobservable factors. Since the process is lengthy, a simple flow chart with the key steps pertaining to factor analysis is shown in Figure 4.4. Figure 4.4 is used to illustrate the overall process; however, the steps are only discussed in limited detail through the remainder of this section. Detailed calculation steps of factor analysis can be found in Pett et al. (2003).

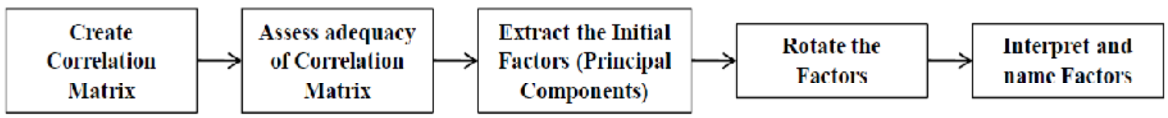


Figure 4.4: Flow chart of Factor Analysis Steps

The Kaiser-Meyer-Olkin (KMO) measure of sampling was used to determine whether or not the data sample was acceptable for factor analysis. Kaiser (1974) recommends a KMO value greater than 0.50. The KMO for the correlation matrix for this research data was 0.60, which suggests it is acceptable to perform factor analysis.

Once it has been determined the data set is adequate, factor analysis is essentially a two-step process. SAS was used to perform the factor analysis for this research. First, the elements are resolved into their principal components (step 3 in Figure 4.4). This is accomplished by transforming the data into orthogonal variables using the eigenvectors of the matrices of the original variables. Each principal component is a linear transformation of original variables. Because the linear components are orthogonal, no independence or multicollinearity exists in the transformed data (Trost and Oberlender 2003; Field 2005).

Once the principal components are determined, a factor rotation is performed (step 4 in Figure 4.4). Factor rotation involves rotating the principal components about the axis of original variables. The factor rotation preserves the orthogonality of the principal components, but a new transformation matrix is formed with each rotation. A method known as maximum variance (varimax) was used in this research. This method maximizes factor loading onto each factor, resulting in more interpretable groupings of factors (Field 2005). A factor loading is the correlation between the presumed factor and the observed variable. A separate rotated factor loading matrix was created for both the starting time variation and the task duration variation (Table 4.4 and Table 4.5 respectively).

Nine factors accounted for 74% of the overall variance of the starting time variation data. Initially, a factor loading threshold of 0.40 was used; however, the threshold was lowered to 0.30 for factors eight and nine. This was a subjective decision by the researcher based on the nature of the causes and how they pertained to the other causes within the factor. There were two causes (lack of instruction on the work method and low morale) that had factor loadings of 0.339 and 0.305 respectively for factor eight. Since both of these causes could be associated with labor force management (i.e. the name selected for factor eight), the threshold was lowered to 0.30. For factor nine, the threshold was lowered to 0.30 because there was only one cause (availability of a crane or forklift) with a factor loading greater than 0.40. Lowering the threshold to 0.30 enabled three other causes to be included with factor nine. A description of the nine factors is provided below.

Factor 1: Senior Management Coordination: The individual causes that loaded this factor were the jobsite being overcrowded, over commitment (i.e. having more work scheduled during the week than is feasible to accomplish), weather, coordinating the work space and sequence of different trades, communication between the owner and project manager, and the impacts of changes in the scope of work. With the exception of weather, all of these causes are generally associated with senior management.

Table 4.4: Rotated Factor Loading Matrix for Starting Time Variation

Variable	Factor 1 Senior Mgmt Coordination	Factor 2 Material Management	Factor 3 Prerequisites & Constructability	Factor 4 Crew Management	Factor 5 Tools & PPE	Factor 6 Supervisor Skills & Communication	Factor 7 Standards & Complexity	Factor 8 Labor Force Management	Factor 9 Equipment Coordination
Overcrowded	0.758	0.021	0.123	0.129	-0.066	0.251	0.085	-0.066	0.099
Overcommitment	0.752	0.278	0.016	0.103	0.074	0.131	0.046	0.009	0.177
Weather	0.716	-0.037	0.238	0.004	-0.048	-0.067	-0.023	0.066	-0.043
TradeCoord	0.711	-0.013	0.101	0.319	-0.024	0.187	0.009	0.067	0.149
OwnerPMCommo	0.640	0.488	0.052	0.009	-0.097	0.236	-0.012	0.030	-0.081
ChangeScope	0.612	0.535	0.097	0.058	-0.044	0.253	0.022	-0.108	0.202
MatlArriveSupply	0.129	0.935	-0.022	-0.018	0.079	0.023	-0.044	-0.049	0.034
WaitForAns	0.278	0.869	-0.085	0.030	0.003	-0.023	-0.028	0.070	-0.015
WorkSequence	-0.002	0.748	0.421	-0.077	0.060	0.077	0.018	-0.084	-0.023
Rework	0.211	0.023	0.753	-0.056	-0.031	0.058	-0.037	-0.022	0.071
Inspection	0.294	0.023	0.733	0.017	0.031	-0.141	0.148	-0.032	-0.058
LowRepitition	0.075	0.084	0.667	0.278	-0.089	0.247	0.338	-0.144	-0.081
PrevWkQual	0.102	0.052	0.645	0.238	-0.075	0.088	-0.074	0.213	-0.103
CompPrevWk	0.026	0.027	0.621	0.123	0.052	0.001	-0.189	0.413	-0.107
Constructability	0.510	0.083	0.594	0.191	-0.009	-0.122	0.143	0.111	0.053
CrewSize	0.087	0.052	0.014	0.671	0.305	0.058	0.115	0.095	0.256
PersTurnover	0.200	0.058	0.152	0.639	0.158	-0.044	0.078	0.184	0.144
LearningCurve	0.123	0.032	0.196	0.599	0.439	0.083	0.167	0.315	0.023
HandTools	0.035	0.128	0.008	0.091	0.890	0.100	0.016	0.072	0.051
PPE	0.071	0.075	-0.046	0.137	0.806	-0.029	0.004	0.132	0.005
PowerTools	-0.057	0.008	0.075	0.319	0.639	0.109	0.113	-0.035	0.079
LackFMSkill	0.166	-0.026	0.032	0.149	-0.063	0.796	-0.141	0.166	-0.006
SiteLayout	0.166	-0.080	0.066	-0.056	0.031	0.581	0.190	0.103	0.350
ForemanWorkerCommo	0.055	-0.042	0.017	0.026	0.064	0.494	0.096	0.031	0.111
FMAvailability	0.144	0.112	-0.051	0.508	-0.062	0.484	-0.119	0.027	-0.194
PMForemanCommo	0.117	-0.015	0.202	0.102	0.084	0.474	0.054	-0.231	-0.032
StrictSpecs	-0.001	-0.015	0.025	0.094	-0.046	0.099	0.819	0.059	0.138
QualityControl	0.165	0.080	-0.067	0.001	0.215	0.018	0.754	0.081	-0.056
WorkComplexity	0.031	0.109	0.080	0.563	-0.049	-0.022	0.462	0.092	0.040
WorkerExp	0.043	0.127	0.019	0.266	0.257	0.256	0.133	0.516	0.104
Socializing	0.111	-0.026	0.160	0.110	0.124	0.081	0.222	0.510	0.038
PeopleLateEarly	0.007	0.108	0.108	0.114	0.130	-0.048	-0.004	0.464	0.173
LackInstrWkMethod	-0.037	0.007	0.546	-0.038	-0.006	0.145	-0.056	0.339	0.002
LowMorale	-0.027	0.407	0.033	0.337	0.337	0.087	0.096	0.305	-0.123
CraneForklift	0.025	0.034	-0.082	0.102	0.095	0.012	0.020	0.126	0.554
FMCommoSkills	0.118	0.022	0.060	0.157	-0.041	0.221	-0.073	-0.094	0.361
GettingMoved	-0.038	0.029	0.063	0.147	0.114	0.321	0.313	0.051	0.348
LackGuidSuperv	0.272	-0.089	-0.128	-0.092	0.342	0.111	-0.032	0.147	0.333
Cumulative Variance	**0.2302**	**0.3438**	**0.4339**	**0.5137**	**0.5694**	**0.622**	**0.6679**	**0.7043**	**0.7379**

Factor 2: Material Management: Material management is essential because when materials do not arrive from a supplier, people need to wait and the work sequence can be affected.

Factor 3: Prerequisites and Constructability: This factor contained several causes of variation pertaining to prerequisites, such as rework, waiting for an inspection, the quality of the previous work, and the completion of previous work.

Factor 4: Crew Management: The crew size, personnel turnover, and the learning curve are all associated with crew management.

Factor 5: Tools and PPE: The name for this factor is fairly self explanatory. Availability and serviceability of hand tools, PPE, and power tools is important.

Factor 6: Supervisor Skills and Communication: Four of the five causes in this factor deal directly with supervisor skills and communication. Foremen skills, their availability, and their communication (with both the worker and the project manager) are all included in this factor.

Factor 7: Standards and Complexity: Strict specifications, quality control, and work complexity are the three causes that loaded this factor. When either the specifications are strict or complexity is high, it makes sense there will likely be a greater quality control requirement.

Factor 8: Labor Force Management: Worker experience, socializing, people arriving late and/or leaving early, lacking instruction on the work method, and morale are all associated with the management of the labor force.

Factor 9: Equipment Coordination: This factor was named after the availability of the crane or forklift because it was the only cause that had a factor loading of greater than 0.40. The other items (foreman communication skills, getting moved before a task is completed, and lacking guidance or supervision) were included as they are related to each other and still had a relatively high loading (all > 0.30).

Table 4.5: Rotated Factor Loading Matrix for Task Duration Variation

Variable	Factor 1 Prerequisites & Constructability	Factor 2 Labor Force Capabilities	Factor 3 Supervisor Skills & Communication	Factor 4 Personnel Management	Factor 5 Standards & Quality Control	Factor 6 Tools & Consumables	Factor 7 Material Management	Factor 8 Weather and Trade Coordination	Factor 9 Equipment Management
Constructability	0.866	-0.137	-0.135	-0.170	0.179	0.012	0.062	-0.149	0.075
LowRepitition	0.858	-0.224	-0.076	0.056	-0.071	-0.026	-0.068	0.042	-0.141
Rework	0.849	-0.336	-0.004	-0.032	0.088	0.063	0.000	0.104	-0.005
PrevWkQual	0.845	-0.365	-0.135	0.064	-0.048	0.109	0.069	0.069	0.035
ChangeScope	0.827	-0.028	0.067	-0.265	-0.328	-0.122	0.040	-0.028	-0.071
Inspection	0.824	-0.390	-0.233	-0.055	-0.003	0.064	0.026	0.028	-0.176
ObtainPermit	0.820	-0.453	-0.238	-0.092	-0.009	0.101	0.055	-0.064	-0.009
LackInstrWkMethod	0.756	-0.120	-0.120	0.353	-0.009	0.008	-0.086	0.095	0.172
DesignDrawError	0.730	-0.209	-0.060	-0.032	0.272	-0.137	-0.170	-0.129	0.010
WorkSequence	0.715	0.017	-0.201	-0.028	0.039	-0.164	-0.246	-0.012	-0.334
GettingMoved	0.263	0.620	-0.197	-0.301	-0.023	-0.024	0.023	-0.100	-0.163
WorkComplexity	0.346	0.564	0.203	-0.086	0.266	-0.154	-0.226	0.172	0.086
CrewSize	0.269	0.562	-0.257	0.313	-0.388	-0.152	-0.203	-0.019	0.116
WorkerExp	0.253	0.561	-0.159	0.496	-0.136	0.088	-0.073	0.054	-0.096
PPE	0.145	0.531	-0.292	-0.492	0.034	0.202	-0.117	-0.083	0.021
LearningCurve	0.231	0.518	-0.158	0.665	-0.087	-0.003	0.016	-0.017	-0.019
LackFMSkill	0.187	0.184	0.602	0.096	-0.209	0.069	0.159	-0.186	-0.051
FMAvailability	0.223	0.223	0.567	0.048	-0.207	0.122	0.230	-0.247	-0.011
FMCommoSkills	0.289	0.341	0.529	-0.090	-0.026	-0.119	0.135	-0.007	0.084
ForemanWorkerCommo	0.151	0.093	0.465	0.134	-0.088	0.311	-0.364	-0.108	-0.073
PeopleLateEarly	0.101	0.370	-0.071	0.299	0.298	-0.056	0.327	-0.054	-0.265
PersTurnover	0.690	0.144	-0.332	0.291	0.062	-0.016	0.029	-0.123	0.128
Socializing	0.061	0.254	0.042	0.253	0.340	0.194	-0.007	0.077	0.015
Absenteeism	0.164	0.488	-0.287	0.201	-0.072	-0.034	0.239	0.171	-0.246
StrictSpecs	0.229	0.467	0.023	-0.249	0.542	-0.121	-0.093	-0.034	0.103
QuesAnsTime	0.564	-0.270	0.058	0.084	0.415	-0.146	-0.056	-0.067	0.043
QualityControl	0.254	0.249	0.379	0.026	0.317	-0.261	-0.300	0.193	-0.042
Consumables	0.017	0.048	0.108	0.077	0.040	0.487	-0.170	0.232	0.090
HandTools	0.114	0.353	-0.119	-0.269	-0.091	0.424	-0.143	0.046	-0.020
LackGuidSuperv	0.018	0.215	0.204	-0.015	0.093	0.422	0.051	-0.063	-0.012
CompPrevWk	0.775	-0.348	-0.137	-0.028	0.049	0.311	0.107	0.124	-0.036
PowerTools	0.113	0.493	-0.232	-0.414	0.047	0.306	-0.119	0.052	0.006
MatlArriveSupply	0.485	0.119	0.134	-0.218	0.133	0.149	0.345	0.019	0.057
WaitForAnsw	0.390	-0.093	0.267	0.119	0.244	-0.025	0.261	-0.193	-0.014
MatlTypeError	0.142	0.179	0.250	0.105	0.192	0.023	0.232	0.349	0.036
Weather	0.555	-0.260	0.002	0.147	-0.098	0.059	-0.043	0.292	0.181
TradeCoord	0.599	0.338	0.043	-0.267	-0.376	-0.347	0.159	0.240	0.156
HeavyEquip	0.520	0.246	-0.180	0.199	-0.036	0.094	0.208	-0.177	0.418
PersLift	0.080	0.481	-0.417	0.090	-0.156	0.089	-0.105	-0.146	0.298
Cumulative Variance	**0.286**	**0.434**	**0.525**	**0.592**	**0.646**	**0.691**	**0.731**	**0.762**	**0.792**

The nine factors identified accounted for 79% of the overall variance of the task duration variation data. As with the starting time variation, an initial factor loading threshold of 0.40 was used; however, the threshold was relaxed based on the nature of the causes and how they pertained to each other within each factor. There were only four individual causes that provided significant loading to Factor 4 for example. Since all four were related to one another and their loadings were relatively high compared to the loading of the other causes, these four causes were chosen to represent the "personnel management" factor.

Although they are in a different order, the overall factors are very similar to the ones identified when analyzing the starting time variation. Therefore, only the first three factors are discussed in detail.

Factor 1: Prerequisites and Constructability: This factor is similar to Factor 3 from the ST variation analysis, but it contains some additional causes such as obtaining a permit and errors with the design or drawing.

Factor 2: Labor Force Capabilities: This is similar to Factor 8 (Labor Force Management) in the ST variation analysis, but this factor is labeled "capabilities" due to the causes of job complexity, worker experience, and having a learning curve.

Factor 3: Supervisor Skills and Communication: All four of the causes in this factor relate directly with the foreman's skill, availability, and communication abilities.

4.1.3 Variation Survey Validation

Separate interviews were conducted with a foreman from a masonry company and a project manager from a concrete company about the results of the survey. Both had over 20 years of experience in the construction industry and neither knew the results of the survey. They were asked what their top three causes of variation were. One responded with equipment availability, weather, and personnel (availability and training). The other replied with completion of previous work ("the trade before me isn't done when they are supposed to be"), weather, and availability of trained craftsmen. Both of their responses are consistent with the top causes identified in this research, which does provide a level of validation. To further validate the results, the case studies were conducted to gather empirical data pertaining to variation of construction related tasks.

4.1.4 Variation Survey Discussion and Conclusions

Previous research focused on variation of task starting times and duration has not been conducted. This study identified the top individual causes of variation, which account for approximately 19 hours of variation per week. This magnitude of variation suggests a weekly schedule reliability of about 52%, which is consistent with previous research (Ballard, 2000). The top individual causes of variation when looking at both starting time and task duration 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.

Factor analysis was performed on the 50 individual causes of variation and identified nine factors that account for approximately 75% of the variance in the data. These nine factors were associated with: Senior Management Coordination, Material Management, Prerequisites and Constructability, Crew Management, Tools and PPE, Supervisor Skills and Communication, Standards and Complexity, Labor Force Management, and Equipment Coordination.

Many of the issues identified in this research are associated with schedule reliability and an inability to ensure laborers have the necessary tools, equipment, and guidance in order to do their work. One goal of planning is to reduce uncertainty and develop a reliable schedule that enables work to be conducted on the planned task during the time which it is scheduled. Figure 4.5 provides a conceptual illustration of this “targeted” work. Variation can cause the work to become off target in terms of the planned task or the schedule. For example, variation can cause work to be conducted on a task that was not scheduled for a number of potential reasons (prerequisite work wasn’t done, there is a question with the design or drawing, materials are not available, etc.). Likewise, variation could cause work to become behind or ahead of the planned schedule. The goal is to develop a planning system that results in the target on the far right of Figure 4.5: Conceptual “Target” for Scheduled or Planned Work – an accurate and precise schedule in which there is little variation from the planned task or the planned schedule.

The use of the planning strategy outlined in Figure 4.6 as a result of this research should assist in creating a more reliable schedule and reduce or eliminate many causes of variation. The factors identified during factor analysis, coupled with the top individual causes of variation, should be used when planning the weekly work. The researcher recommend the use of the LPS® while using the factors identified in Figure 4.6 as the initial basis for planning. The LPS® includes a 6 week look-ahead process in which constraints on successful task execution are identified and removed, or else the task is not available to be included on weekly work plans.

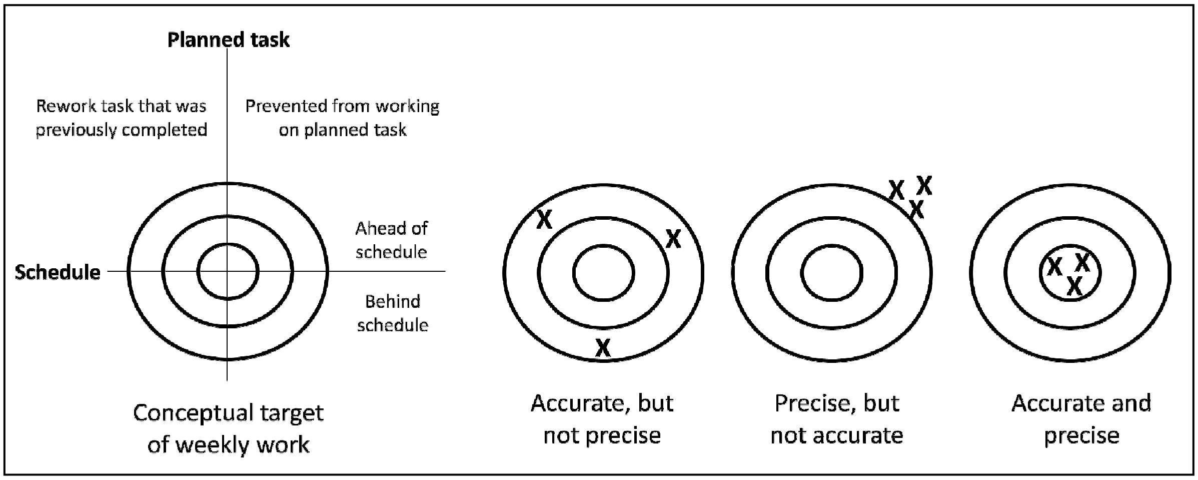


Figure 4.5: Conceptual "Target" for Scheduled or Planned Work

The primary focus of the planning sessions should be tailored to the number of trades involved with the project. For projects with a small number of trades (where inter-trade coordination is not as large of an issue), the planning session should focus on the labor force, equipment coordination and management, tools and PPE, and material management. It is recommended the labor force factor be the primary focus based on the factor analysis results and because three of the top individual causes of variation deal with the labor force. For projects involving multiple trades, the planning strategy should be expanded to encompass all of the factors identified during the factor analysis. The results of this research indicate the primary factors to focus on during planning are labor force, senior management coordination, supervisor skills and communication, crew management, and prerequisites and constructability. The heavier shaded lines in Figure 4.6 indicate the primary factors associated with the planning effort for projects with few and multiple trades.

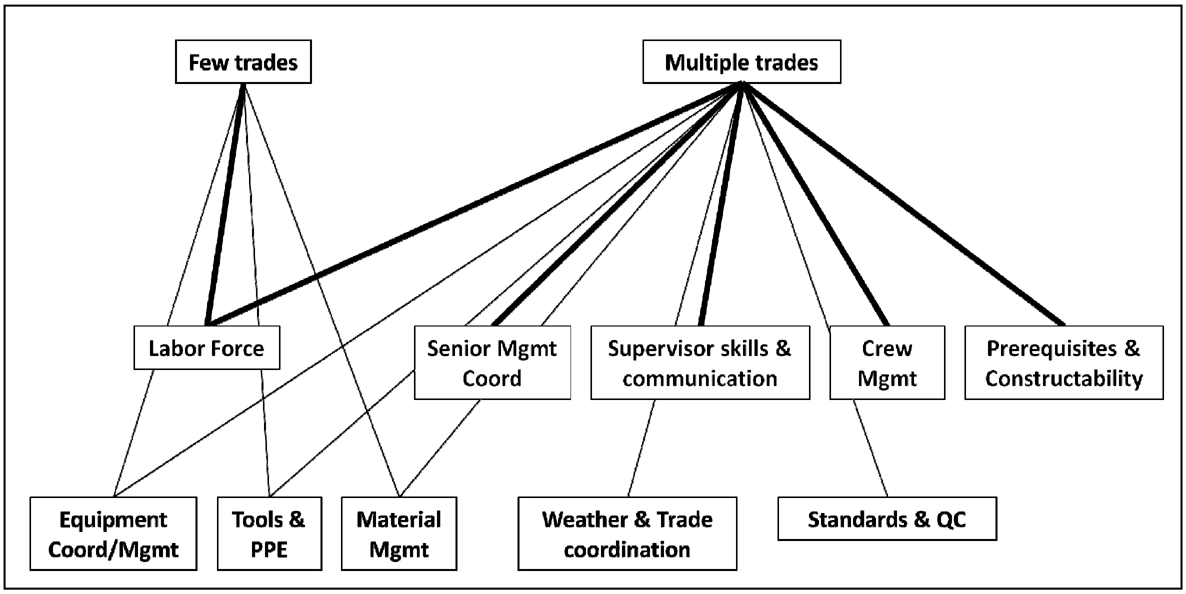


Figure 4.6: Concept Map for Recommended Factors to Consider when Developing Weekly Work Plans Based on the Number of Trades Involved with the Project

4.2 Case Study 1

4.2.1 Case Study 1 Results

This study involved a general contractor responsible for the synchronization of 43 different trades constructing a $50M data center. The GC's work breakdown structure identified 1183 tasks performed by the various trades working on the data center. If there was either starting time and/or task duration variation associated with a task, an attempt was made to capture the reason. Figure 4.7 shows the 13 different causes of variation and the number of times they occurred over the 28 week period.

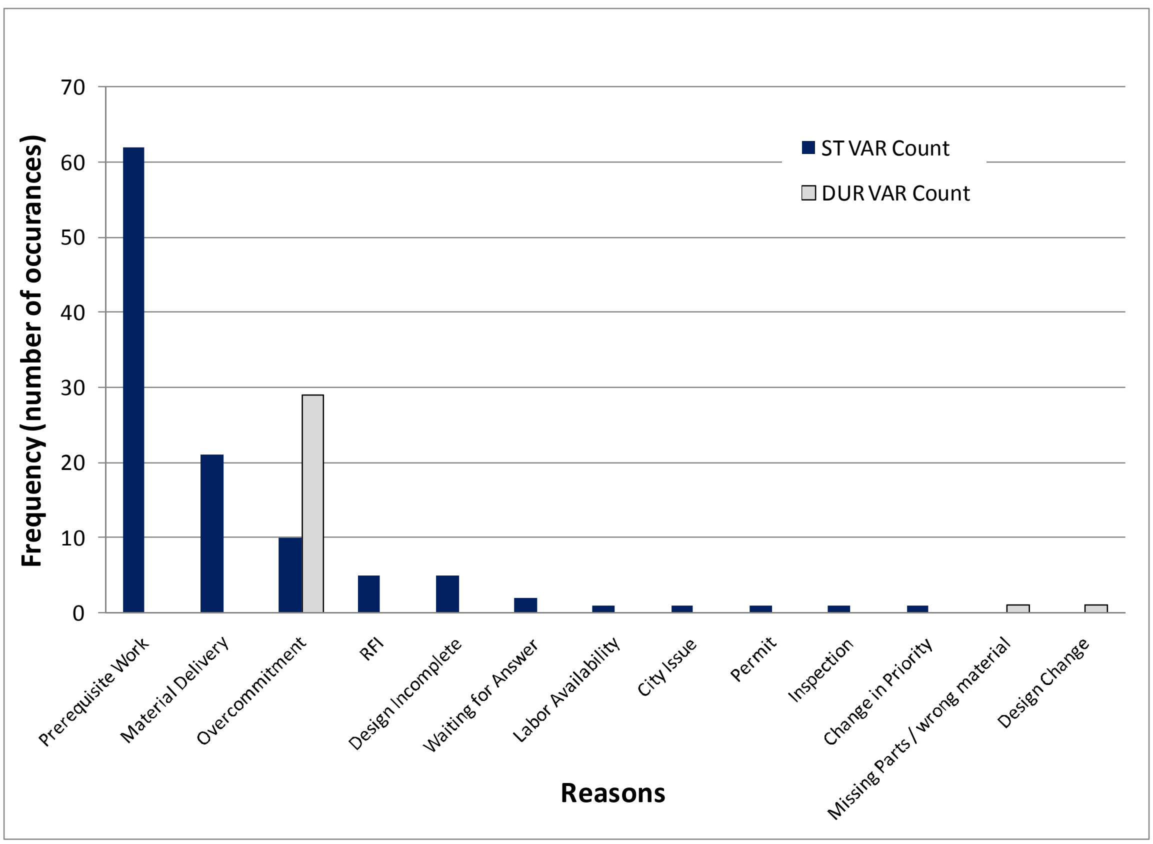


Figure 4.7: Pareto Chart of Variation Reasons

4.2.2 Case Study 1 Analysis

Objective 3: Determine the causes of variation that pose the greatest risk of impacting project performance.

The frequency alone does not provide enough information about which causes of variation are posing the greatest risk to the project. In order to determine risk, both frequency and severity are required; therefore, a risk assessment matrix was used to illustrate the variation data (Figure 4.8). Each point in the figure represents one cause of variation. The horizontal axis is the normalized frequency. Each frequency of each cause of variation was normalized by the total number of variation occurrences. In other words, the horizontal axis represents the percent of variation that is accounted for by each cause. The vertical axis is the mean magnitude (in days) resulting from each cause of variation.

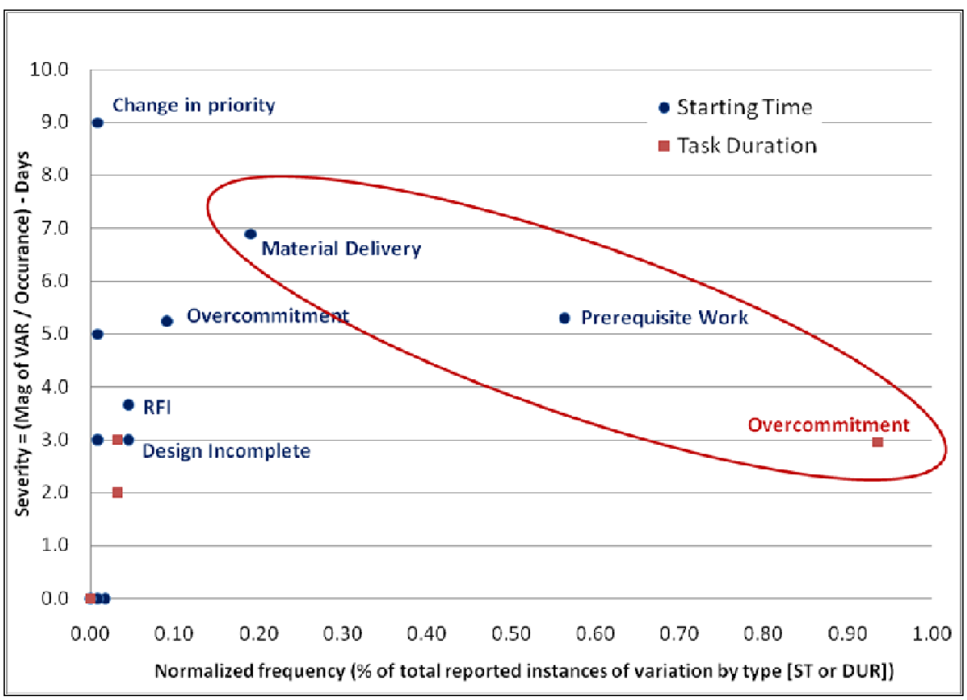


Figure 4.8: Starting Time and Task Duration Variation on Risk Assessment Matrix

Overcommitment by a subcontractor, incomplete prerequisite work, and a lack of materials, shown in Figure 4.8, were the three dominating causes of variation that comprise the risk frontier to project performance. Overcommitment accounted for almost all of the instances of task duration variation and was arguably the greatest risk to schedule compliance. When one trade over commits (i.e. plans to accomplish more than they actually do), it often affects the sequential trade(s) behind them; thus causing them to experience starting time variation due to the prerequisite work that was not completed.

Two additional causes of variation to highlight were requests for information and problems associated with the design being incomplete. The results are fairly consistent with the survey results, specifically the concept map in Figure 4.6, based on the factor analysis of the top causes of variation identified in the variation survey. Since multiple trades were involved with this case study project, Figure 4.6 is modified to highlight the results of this case study (Figure 4.9).

Overcommitment occurs when a foreman over estimates what his crew(s) will accomplish and is a combination of supervisor skills and crew management in Figure 4.9. The other causes of variation determined in this research to pose the greatest risk are also depicted in Figure 4.9.

Information is to reduce uncertainty. Galbraith (1977) introduced the concept of the "uncertainty gap", between the information required to build a technical system and the information available in the project organization to do so. Dia et al. (2009) also found waiting for answers to questions about the design, regarding complexity or unpredictability, to be one of the top factors affecting productivity based on their survey of craft workers.

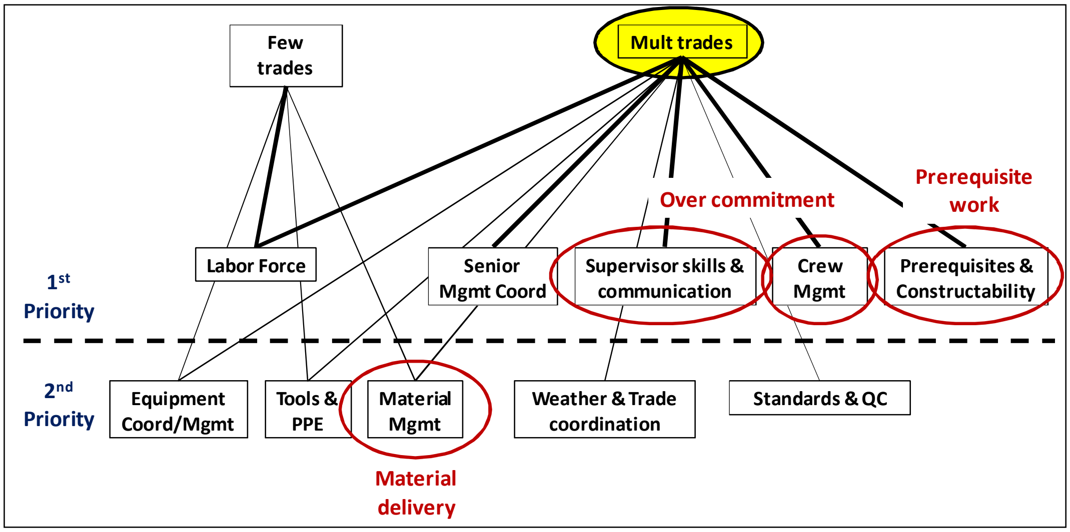


Figure 4.9: Concept Map for Factors Causing Variation Based on the Number of Trades Involved (Modified Version of Figure 4.6)

Objective 4) Identify the organizational social network of trades existing among a construction project.

Objective 5) Analyze the social network to identify the key trades within the network.

In order for a project manager to effectively target the variation for reduction, it is important to understand the social network of trades that exists in a project. The project was divided into 14 separate project area and since the process of identifying the social networks is repetitive, the steps are only shown for the first area (i.e. "Site Work"). The initial step was to create a matrix that illustrated which trades worked during each of the 28 weeks. This matrix is denoted [W] for weekly work matrix. The [W] for the "Site Work" area is shown in Figure 4.10. The trades are listed along the left hand side and the weeks are listed across the top. A “1” indicates the trade worked in the respective area during that week and a “0” indicates the trade did not work. Consider the first two trades in Figure 4.10 as an example. Trade “N” worked in all weeks, except for 3, 6, 24, 26, and 28. Trade “DD” only worked in weeks 27 and 28.

Contractor	Wk1	Wk2	Wk3	Wk4	Wk5	Wk6	Wk7	Wk8	Wk9	Wk10	Wk11	Wk12	Wk13	Wk14	Wk15	Wk16	Wk17	Wk18	Wk19	Wk20	Wk21	Wk22	Wk23	Wk24	Wk25	Wk26	Wk27	Wk28
N	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	0
DD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
V	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
B	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HH	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1
Z	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0
W	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
P	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
II	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
CC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
KK	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
MM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
E	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 4.10: Weekly Work Matrix for the “Site Work” Area

An adjacency matrix was created by multiplying [W] by its transpose [W^T] and replacing the diagonal with zeros (Figure 4.11). Mathematically, an adjacency matrix is a means of representing which vertices of a graph are adjacent to which other vertices. In this research, [A] indicates how many times each trade worked with the others and is the basis for the social network. Consider trade “N” in the first row of [A]. Trade “N” worked with “DD” one time, with “V” 13 times, with “K” and “B” one time each, etc. Zeros are placed along the diagonal because trades are not considered to work with themselves.

The adjacency matrices in this research are undirected. In other words, the order of the pairings of trades is irrelevant. The [W] indicates which trades are physically working in the same area, not whether the tasks they are performing are related in a sequential or simultaneous manner. The adjacency matrix is also symmetric; therefore, it has a complete set of real eigenvalues and an orthogonal eigenvector basis (Das 2010, Ghosh et al. 2010). These characteristics will be more important when centrality is discussed later in this section.

	N	DD	V	K	B	HH	Z	W	AA	P	II	O	CC	KK	MM	G	E	L	M
N	0	1	13	1	1	5	11	4	1	2	2	2	2	4	1	2	2	2	2
DD	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
V	13	0	0	1	1	4	8	3	1	1	1	2	2	4	0	0	3	2	2
K	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0
B	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
HH	5	2	4	0	0	0	0	2	0	0	0	0	0	3	0	1	0	2	1
Z	11	0	8	0	1	0	0	1	0	2	2	0	0	0	1	0	1	0	0
W	4	0	3	0	0	2	1	0	0	0	0	0	0	1	0	0	0	1	1
AA	1	0	1	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	0
P	2	0	1	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0
II	2	0	1	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0
O	2	0	2	1	0	0	0	0	1	0	0	0	2	1	0	0	2	0	0
CC	2	0	2	1	0	0	0	0	1	0	0	2	0	1	0	0	2	0	0
KK	4	0	4	0	0	3	0	1	1	0	0	1	1	0	0	0	1	2	1
MM	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
G	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
E	2	0	3	1	0	0	1	0	1	0	0	2	2	1	0	0	0	0	0
L	2	0	2	0	0	2	0	1	0	0	0	0	0	2	0	0	0	0	1
M	2	0	2	0	0	1	0	1	0	0	0	0	0	1	0	0	0	1	0

Figure 4.11: Adjacency Matrix for “Site Work” Area

Pajek®, a social network analysis software, was used to create the social networks in this research. The steps for creating a Pajek® input file are fully outlined in Part I of De Nooy et al. (2005), but a partial listing of the “Site Work” input file is shown below in Figure 4.12. Each of the vertices (19 of them in the “Site Work” area) are labeled and provided three dimensional coordinates, which are used to initially locate the vertices. The second portion of the input files described the edges (or relationships) between the vertices. For example, the first three edges listed in Figure 4.12 indicates that the first trade (N in this example) is linked to trades 2, 3, and 4 (i.e. trades DD, V, and K) by strengths of 1, 13, and 1 respectively. Notice that this is the start of the first line of the [A] (Figure 4.11).

```
*Vertices    19
1 "N"        0.7842    0.6742    0.5000
2 "DD"       0.2643    0.2643    0.5000
3 "V"        0.3724    0.8080    0.5000
--- vertices 4-16 omitted to save space
17 "E"       0.7842    0.3258    0.5000
18 "L"       0.4738    0.1677    0.5000
19 "M"       0.2158    0.3258    0.5000
*Edges
1 2 1
1 3 13
1 4 1
--- likewise for the remainder of [A]
```

Figure 4.12: Partial listing of Pajek® Input File for “Site Work” Area

The adjacency matrix provides the majority of the input data that enables Pajek® to create the graphical depiction of the social network (Figure 4.13). Graphically, a trade is represented as a vertex. Two vertices (or trades) are adjacent if they are two end-vertices of an edge (or a connection) and two edges are adjacent if they share a common end-vertex. The numbers next to the lines are line values and represent the strength of the relationship (De Nooy 2005).

The diagram itself starts to provide some insight into the key members of the social network. The trades with more ties to others are more centrally located and the stronger the tie (i.e. the more often trades work together); the closer their vertices are to one another. Trades with less ties and/or weaker ties, tend to be located more around the periphery of the network. Topologically, trade N is located at the center of the network because N is the only trade that has ties to each of the other 18 trades. Upon visual comparison of trade N with trades HH, KK, V, Z, one can start to visualize a 2^{nd} tier of centrality with the latter four trades. They are less connected to the entire network than trade N; however, they are still important as they may be critical links between members otherwise not connected. For example, trades DD and M do not have a direct tie, but they are both connected to trade HH; thus trade HH could be a critical link between trades DD and M. The second objective uses more than simple visual techniques to identify the key trades within the network.

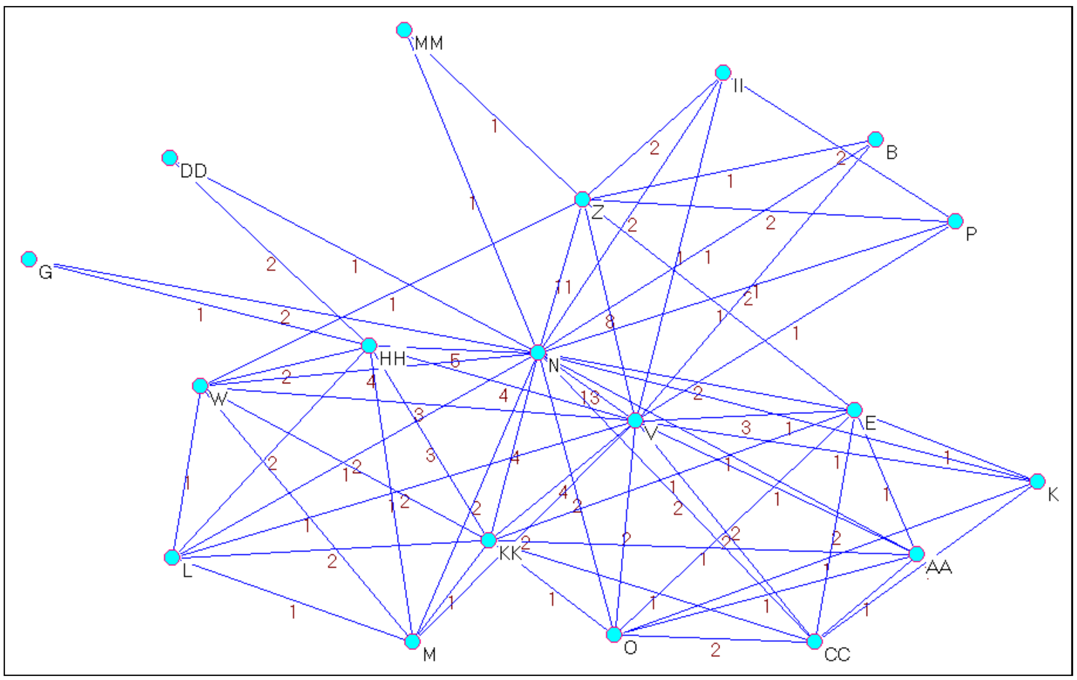


Figure 4.13: Social Network for “Site Work” Area

Exploring a network structure by calculation is much more concise and precise than visual inspection (De Nooy et al. 2005). Centrality is a key measure that reflects the distribution of relationships through the network. In a highly centralized network, a small percentage of the members will have a high percentage of relationships with other members in the network (Chinowski et al. 2010). One of the most used centrality measures is the "degree centrality," which is a fundamental quantity describing the topology of scale-free networks. Degree centrality can be interpreted as a measure of immediate influence, as opposed to long-term effect in the network (Estrada and Rodríguez-Velázquez, 2005). Degree centrality was used in the previously identified construction related SNA [Thorpe and Meade (2001), Chinowski et al. (2008 and 2010), and Di Marco (2010)]; therefore, it was included with this research as well.

Eigenvector centrality is better interpreted as an extended degree centrality which is proportional to the sum of the centralities of the node' neighbors (Estrada and Rodríguez-Velázquez, 2005). In other words, eigenvector centrality takes into consideration the centrality of the other trades to which one is connected. No other instances could be found in which eigenvector centrality analysis was used to identify the key members in a social network for construction related research, therefore this method was examined for potential utility.

The associated relative degree of centrality is calculated by dividing the individual degree of centrality by the number of other individuals in the network (Di Marco et al. 2010). Consider trade G (located on the far left) in the "Site Work" social network (Figure 4.13 and Figure 4.13) as an example. The individual degree of trade G is two, since G has ties to two other trades (HH and N). There are a total of 19 trades in the network, so there are 18 (i.e. n-1) other trades in which trade G could have ties to. The relative degree of centrality for trade G is then 2/18 or 0.11 (note the value in row G under Site Work in Table 4.6). A high centrality value indicates the trade has a greater number of ties to other members of the network. Consider the centrality values of the five highlighted trades (B, DD, K, N, and V) in Table

4.6. These five trades are the only ones with a frequency $\geq$ 10 and all of their centrality values are relatively high compared to most of the other trades; thus they are more central to the social network. Table 4.6 also enables one to compare centrality values for each of the 14 project areas. For example, trade N (centrality value = 1.00) is much more central to the "Site Work" area than trade K (centrality value = 0.28).

The Laplacian matrix was used to generate the eigenvalues and eigenvectors for each of the 14 areas of the project. Among all eigenvalues of the Laplacian matrix of a graph, the most studied is the 2^{nd}, as it represents the algebraic connectivity of a graph (Das 2010). Hagen and Kahng (1992) also stated the 2^{nd} eigenvector is an effective tool to partition or cluster groups of data within a network. To create the Laplacian matrix, one begins with the adjacency matrix [A] (see Figure 4.11). The rows of [A] are summed and placed on the diagonal of the degree matrix, denoted by [D]. The degree matrix is a diagonal matrix of vertex degrees (i.e. the sum of each row of [A]). The degree matrix represents the sum of the total connections for each trade and an example for the "Site Work" area is shown in Figure 4.14.

Table 4.6: Summary of Degree Centrality Analysis

Trade Code	Sitework	Ext Skin Roof	Lab Struct 1&2	Lab Struct M&D	Lab Elect Rms	Lab Fit-out	DC Struct 11&12	DC Struct M&D	DC Elect Rms	DC Fit-out	Admin	Admin - Corridor	Admin - Loading	Admin - Lift	**Frequency**	**Average Centrality**
A				0.54	0.38	0.68				0.63	0.64	0.89	0.50	0.75	8	0.63
AA	0.33	0.18		0.46	0.38	0.27		0.80	0.25						7	0.38
B	0.17			0.54	0.62	0.77		0.50		0.79	0.55	0.83	0.63	0.75	10	0.61
BB						0.82				0.58	0.64				3	0.68
C												0.67	0.25		2	0.46
CC	0.39														1	0.39
D		0.00				0.41				0.37		0.50		0.75	5	0.41
DD	0.11	0.64		0.77	0.31	0.82		0.90	0.67	0.74	0.36	0.44	1.00	0.875	12	0.64
E	0.44														1	0.44
EE									0.42						1	0.42
F						0.59				0.11					2	0.35
FF						0.18				0.21		0.50			3	0.30
G	0.11														1	0.11
GG						0.23									1	0.23
H						0.55			0.42			0.22			3	0.39
HH	0.44	0.18	0.25	0.38	0.46	0.27	1.00	0.50		0.05					9	0.39
I												0.67			1	0.67
II	0.22														1	0.22
J		0.45				0.23				0.26		0.56	0.50	0.25	6	0.38
JJ												0.28			1	0.28
K	0.28	0.64	0.25	0.62	0.15	0.82	0.83	0.60	0.08	0.68	1.00	0.94	0.75		13	0.59
KK	0.56								0.08						2	0.32
L	0.33														1	0.33
LL		0.73													1	0.73
M	0.33														1	0.33
MM	0.11					0.14				0.05	0.55			0.125	5	0.19
N	1.00	0.45	0.00	1.00	0.54	0.82	0.83	1.00	0.33	0.84	0.82	0.83	0.25	0.75	14	0.68
NN										0.37	0.36	0.61			3	0.45
O	0.39			0.69	0.46	0.64		0.70		0.68	0.82	0.78			8	0.64
OO		0.45		0.38	0.08										3	0.31
P	0.22			0.31	0.62		0.33								4	0.37
PP				0.54	0.08		0.67		0.25						4	0.38
Q						0.55						0.06			2	0.30
QQ															0	0.00
R						0.36		0.30	0.58	0.47	0.55	0.72		0.75	7	0.53
S			0.00												1	0.00
T												0.61			1	0.61
U				0.23	0.62	0.55		0.60	0.25	0.58		0.50	0.38	0.75	9	0.49
V	0.83	0.73		0.77	0.08	0.82	0.67	0.90	0.92	0.79	0.91	0.83	0.50		12	0.73
W	0.39	0.82				0.36				0.37					4	0.48
X						0.18				0.11					2	0.14
Y		0.55				0.68			0.25	0.47					4	0.49
Z	0.44		0.00	0.92	0.46		1.00	0.80	0.33		0.27				8	0.53

	N	DD	V	K	B	HH	Z	W	AA	P	II	O	CC	KK	MM	G	E	L	M
N	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DD	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	0	0	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HH	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0
Z	0	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0
W	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0
AA	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0
II	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0
O	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0
CC	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0
KK	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	0
MM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0
L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8

Figure 4.14: Degree Matrix for “Site Work” Area

The Laplacian matrix, denoted by [L], is created by subtracting [A] from [D] (i.e. [L] = [D] – [A]). It is easy to see that [L] is a positive semidefinite symmetric matrix and its rows sum to zero; therefore, [L] is singular (Das, 2010). The Laplacian matrix for the “Site Work” area is shown in Figure 4.15.

	N	DD	V	K	B	HH	Z	W	AA	P	II	O	CC	KK	MM	G	E	L	M
N	58	-1	-13	-1	-1	-5	-11	-4	-1	-2	-2	-2	-2	-4	-1	-2	-2	-2	-2
DD	-1	3	0	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0
V	-13	0	48	-1	-1	-4	-8	-3	-1	-1	-1	-2	-2	-4	0	0	-3	-2	-2
K	-1	0	-1	5	0	0	0	0	0	0	0	-1	-1	0	0	0	-1	0	0
B	-1	0	-1	0	3	0	-1	0	0	0	0	0	0	0	0	0	0	0	0
HH	-5	-2	-4	0	0	20	0	-2	0	0	0	0	0	-3	0	-1	0	-2	-1
Z	-11	0	-8	0	-1	0	27	-1	0	-2	-2	0	0	0	-1	0	-1	0	0
W	-4	0	-3	0	0	-2	-1	13	0	0	0	0	0	-1	0	0	0	-1	-1
AA	-1	0	-1	0	0	0	0	0	6	0	0	-1	-1	-1	0	0	-1	0	0
P	-2	0	-1	0	0	0	-2	0	0	7	-2	0	0	0	0	0	0	0	0
II	-2	0	-1	0	0	0	-2	0	0	-2	7	0	0	0	0	0	0	0	0
O	-2	0	-2	-1	0	0	0	0	-1	0	0	11	-2	-1	0	0	-2	0	0
CC	-2	0	-2	-1	0	0	0	0	-1	0	0	-2	11	-1	0	0	-2	0	0
KK	-4	0	-4	0	0	-3	0	-1	-1	0	0	-1	-1	19	0	0	-1	-2	-1
MM	-1	0	0	0	0	0	-1	0	0	0	0	0	0	0	2	0	0	0	0
G	-2	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	3	0	0	0
E	-2	0	-3	-1	0	0	-1	0	-1	0	0	-2	-2	-1	0	0	13	0	0
L	-2	0	-2	0	0	-2	0	-1	0	0	0	0	0	-2	0	0	0	10	-1
M	-2	0	-2	0	0	-1	0	-1	0	0	0	0	0	-1	0	0	0	-1	8

Figure 4.15: Laplacian Matrix for “Site Work” Area

MatLab and was used to determine the eigenvalues and eigenvectors for the Laplacian matrice of each of the 14 areas. The terms of the 2nd eigenvectors for each of the 14 areas are summarized in Table 4.7. The larger absolute values of the terms identify those trades that are more dominant in the eigenvector. Several terms were close to zero and a plot (not included due to space limitations) was created to determine the threshold of $\pm$ 0.10 for terms to include in the eigenvector analysis. A higher threshold could have been used; however, the intent was to make the analysis more inclusive rather than exclusive. The terms in Table 4.7 that met the threshold of $\pm$ 0.10 are shown in bold and their frequency (i.e. number of project areas the theshold was met) was plotted against the assciated magnitude of centrality for each trade in Figure 4.16.

Table 4.7: Summary of 2nd Eigenvector Terms for Each Project Area

Trade Code	Sitework	Ext Skin Roof	Lab Struct 1&2	Lab Struct M&D	Lab Elect Rms	Lab Fit-out	DC Struct 11&12	DC Struct M&D	DC Elect Rms	DC Fit-out	Admin	Admin - Corridor	Admin - Loading	Admin - Lift
A				-0.004	-0.016	0.025				-0.007	0.045	-0.042	0.045	**-0.184**
AA	-0.005	0.005		**-0.249**	0.008	0.020		**-0.161**	-0.013					
B	-0.004			-0.035	-0.001	**0.176**		-0.033		-0.091	-0.049	**-0.238**	**0.567**	**-0.184**
BB						**-0.838**				-0.025	0.001			
C												-0.013	0.055	
CC	-0.012													
D		0.000				0.007				0.004		-0.030		**-0.184**
DD	-0.012	**-0.731**		**-0.163**	-0.004	**0.238**		**-0.537**	**0.615**	0.020	0.013	-0.018	**-0.661**	**-0.103**
E	-0.001													
EE									0.005					
F						-0.022				-0.007				
FF						-0.004				0.006		-0.004		
G	-0.026													
GG						0.006								
H						0.000			**0.135**			0.002		
HH	-0.045	-0.008	**0.707**	-0.015	-0.014	-0.016	-0.054	-0.019		-0.006				
I												-0.058		
II	-0.015													
J		-0.006				0.006				0.000		0.001	0.053	**0.432**
JJ												0.011		
K	-0.006	-0.019	**0.707**	**-0.188**	0.002	0.064	**0.168**	-0.072	-0.050	**0.347**	**0.284**	**0.190**	**-0.420**	
KK	-0.026								-0.005					
L	-0.010													
LL		**0.647**												
M	-0.011													
MM	-0.011					-0.015				0.012	-0.001	**-0.462**		**0.775**
N	**0.861**	-0.054	0.000	**0.213**	**-0.533**	**0.437**	**0.168**	0.071	**0.123**	**-0.763**	**0.512**	-0.024	0.055	**-0.184**
NN										-0.002	0.013	-0.052		
O	-0.012			**-0.347**	0.047	0.003		-0.030		-0.033	0.034			
OO		-0.006		-0.017	0.002									
P	-0.015			-0.003	**0.805**		**-0.881**							
PP				-0.026	0.000		**0.285**		0.011					
Q						0.000						0.006		
QQ														
R						0.005		0.011	**-0.762**	0.007	-0.001	-0.036		**-0.184**
S			0.000											
T												-0.024		
U				0.004	-0.047	0.011		0.024	-0.063	0.008		-0.033	0.087	**-0.184**
V	**-0.484**	-0.019		**0.841**	0.001	**-0.111**	**0.285**	**0.817**	0.031	**0.535**	**-0.805**	**0.825**	**0.218**	
W	-0.031	**0.208**				0.006				-0.007				
X						-0.006				0.012				
Y		-0.018				0.009			-0.024	-0.011				
Z	**-0.134**		0.000	-0.012	**-0.250**		0.028	-0.071	-0.002		-0.047			

Figure 4.16 expresses the eigenvector analysis results in similar terms to a risk assessment matrix. The trades that were frequently involved with the project areas coupled with larger absolute centrality magnitudes (i.e. furthest from the origin) can be considered

key members of network. Although more trades could be considered to be the "key" ones, four clearly stood apart from the others. They were trades: N (mechanical), V (electrical), K (drywall) and DD (painting).

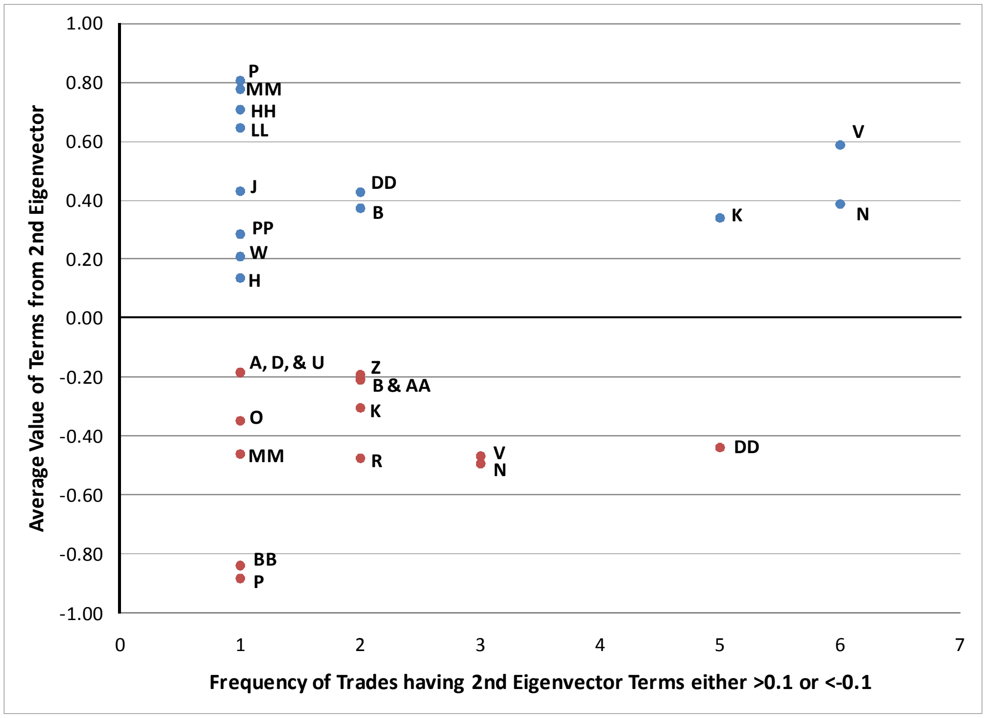


Figure 4.16: Results of 2^{nd} Eigenvector Analysis to Identify Key Trades

The results between the degree and eigenvector centrality are fairly consistent. Figure 4.17 illustrates the degree centrality results in terms of frequency and magnitude. The four key trades identified in the eigenvector centrality analysis are circled for reference and are also the top four trades identified in the degree centrality analysis.

Although the eigenvector centrality analysis is more time consuming, it has merit because it considers the centrality of the other trades when determining the centrality of individual trades. Take trade “P” for example, which worked in four of the 14 project areas. The degree centrality values were 0.22, 0.31, 0.62, and 0.33 (see Table 4.6). When plotted in Figure 4.17, trade “P” doesn’t stand out. When the eigenvector analysis results are examined, trade “P” has values of -0.015, -0.003, 0.805, and -0.881 (Table 4.7). The last two terms are quite significant and this becomes apparent when plotted in Figure 4.16. By using degree and eigenvector centrality analysis, one can identify those trades that are considered to be key, based on the common results of both methods and also identify some trades that may be key only in a couple areas of the project.

Figure 4.17 was also separated by the two diagonal lines shown. The four trades (V, N, DD, and K) to the upper most right of the figure are considered the 1st tier and central most trades of the overall project. The 2nd tier consists of seven trades between the two diagonal lines, which are O, A, B, R, Z, U, and HH. Although these trades are not as central as the 1st tier trades, they are still imporant as they are critical links between several of the remaining trades.

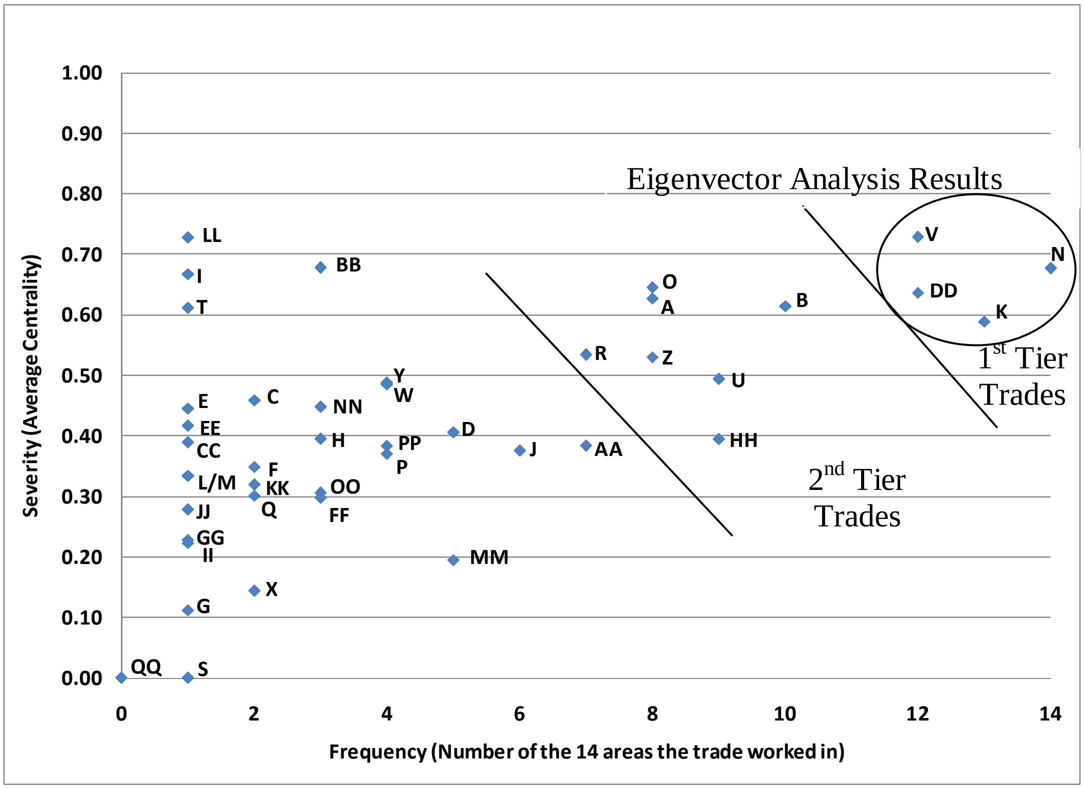


Figure 4.17: Key Trade Summary for All 14 Project Areas

Objective 6: Identify the organizational structure of contractors / trades associated with the variation posing the greatest risk to project performance.

Objective 7: Develop a decision support system to target trades in an effort to reduce variation.

In addition to identifying the primary causes of variation, it is important for project managers to understand the origin of the causes and how the trades are related to one another. These two research objective examine which trades are associated with the top causes of variation and how those trades are related to each other as well as the other trades of this project. The risk assessment matrix (Figure 1.1) is used to illustrate which trades are associated with the top three causes of variation previously identified in this case study. More specifically, which trades are associated with:

- Starting time variation due to prerequisite work not being completed,
- Starting time variation due to materials not being delivered when planned, and
- Task duration variation due to an over commitment by the respective trade.

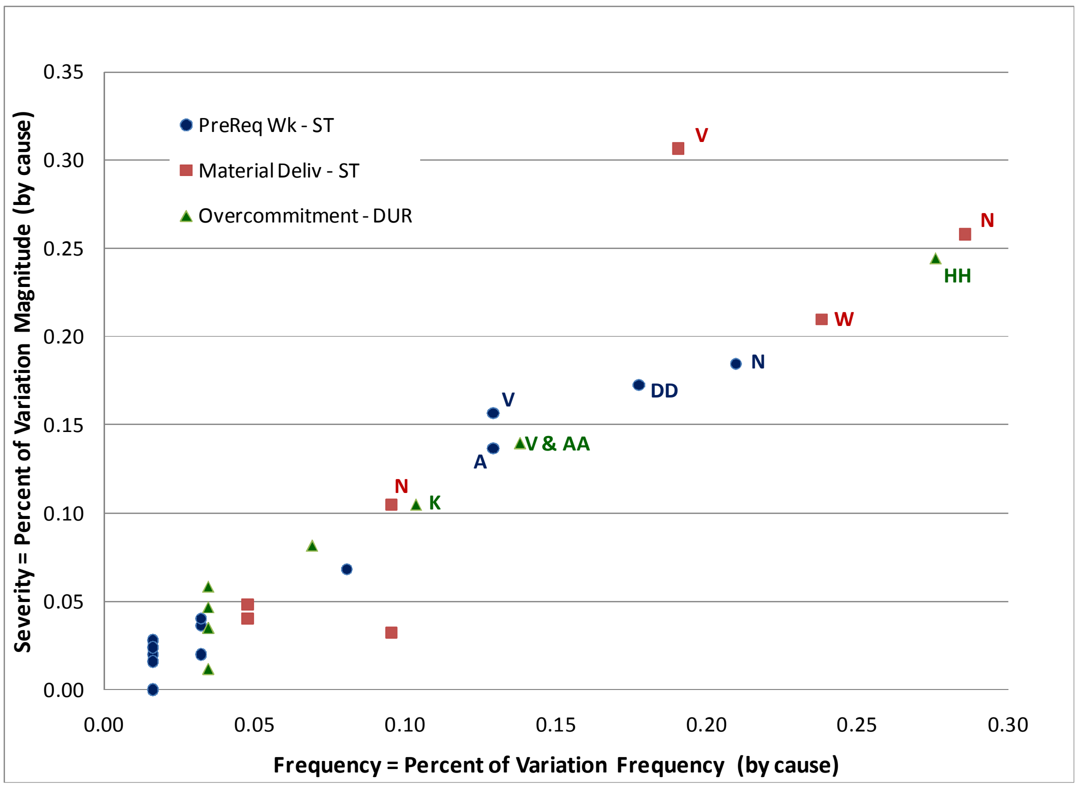


Figure 4.18: Trades Associated with the Top Three Causes of Variation

The horizontal axis of Figure 4.18 represents the percent of time each trade was associated with the frequency of variation occurences and the vertical axis represents the percent of variation magnitude a trade is associated with. Consider trade V and the data point that has the largest severity in Figure 4.18. This point is associated with the starting time variation due to material delivery for trade V. There were 21 instances in which material delivery impacted the starting time of a task during the entire project. Trade V accounted for four (i.e. 19%) of those instances. In terms of magnitude, there were 124 total days of starting time varation associated with material delivery during the entire project. Trade V accounted for 38 (i.e. 31%) of those days.

While Figure 4.18 illustrates the trades that are associated with the greatest risk in terms of frequency and severity of variation, managers need to understand how the trades are related to each other. For example, how critical is it that the steel contractor is associated with the greatest frequency and severity of task duration variation due to over commitement? The final analysis related to this case study was to combine the variation and social network analysis to develop a decision support system focused on reducing variation.

A centrality and variation score was calculated for each trade by using the respective frequency-severity plots (Figure 4.17 and Figure 4.18). The scores were determined by calculating a normalized distance from the origin for both the centrality and the variation. The results were plotted and initially separated into four quadrants (Figure 4.19). The respective trades are also listed for the corresponding code letters of the seven trades with the highest priority for reducing variation. Trades in the upper right hand quadrant of Figure 4.19 are those recommended to be the highest priority for a project management team to reduce variation as they both have high uncertainty (i.e. variation) and high centrality relative to the other trades in the project.

There were no trades that fell in the lower right quadrant and the trades in lower left quadrant have relatively low variation and low centrality. While these trades are still important to the overall project, they are not likely to require the same level of attention from the project management team. There were several trades in the upper left quadrant, therefore that quadrant was divided a second time and five trades (DD, K, A, R, and HH) were identified. Of those five trades, DD has relatively high variation and centrality, therefore is the third overall priority for the project management team. The remaining four trades (K, A, R, and HH) should be considered to pose about the same level of risk for the project management team. While trade K has lower variation, it has a higher level of centrality. On the other hand, trade HH has a higher level of variation, but it is tied to few other trades.

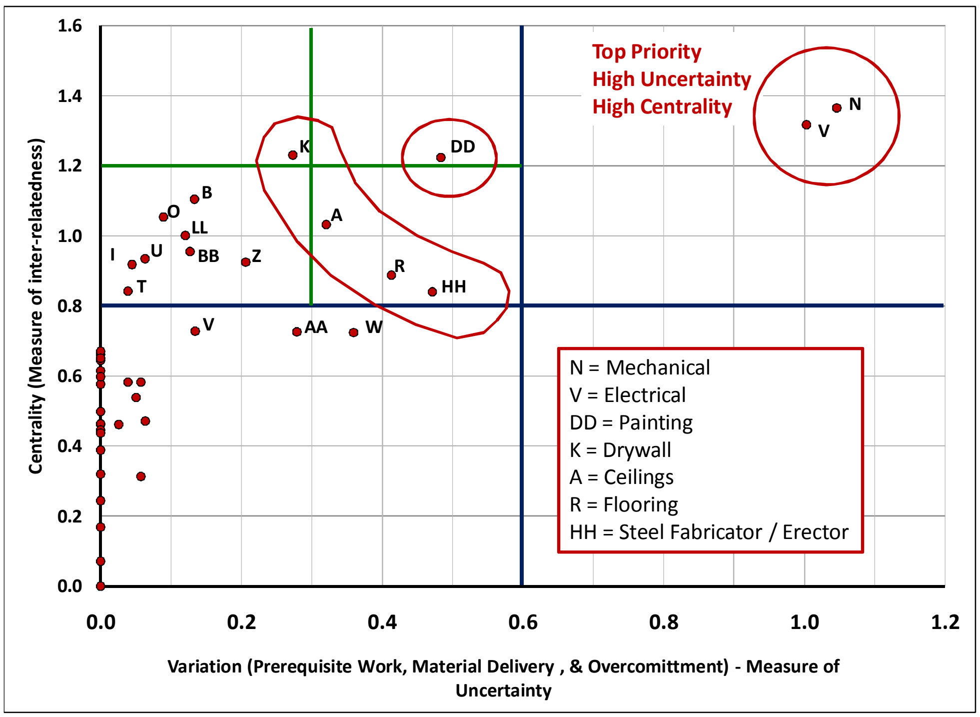


Figure 4.19: Variation vs Centrality Summary for All Trades

In cases like this, when there is a trade-off between frequency and severity, multi-criteria decision making (MCDM) methods can be applied. In this research AHP was used to further prioritize these four trades. The data indicates there is a tradeoff between centrality and variation for trades K, A, R, and HH. AHP is used to support a decision as to how these four trades should be prioritized in an effort to reduce variation. There are four steps associated with the AHP. Each of the steps is outlined the information from this case study.

Step 1) Determine selection criteria weights.

In this step, the relative importance of each of the four selection criteria (variation frequency, variation severity, centrality frequency, and centrality severity) is established. The weights were determined by me while performing a pairwise comparison between each of the criteria individually. A project manager could have also been consulted to determine these priorities; however, since the method of performing the AHP is the critical aspect of this portion of the research, I conducted the pairwise comparison. For example, the relative importance of variation frequency is compared to variation severity, then to centrality frequency, and finally to centrality severity). The relative importance, using a scale of 1-9 to indicate which criterion is favored over the other, was determined by using the Saaty Rating Scale (Table 4.8).

Table 4.8: The Saaty Rating Scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important.	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

Figure 4.20 illustrates the criteria weights for the four selection criteria. In this case, variation frequency was deemed to be between equally important and somewhat more important than variation severity; hence, the pairwise score of 2 in the top row where variation frequency and severity intersect. The weights are determined by normalizing the pairwise comparison matrix by the sum of each column. The rows of the normalized matrix were then averaged to determine the weights for each of the four criteria. The weights are highlighted in the lower right portion of Figure 4.20. The weights are the relative importance for each of the criteria, with respect to one another. Criterion with a higher weight is more important relative to a criterion with a lower weight.

Owner/Mgr Priorities	VAR Freq	VAR Sever	Central Freq	Central Sever	
VAR Freq	1.00	2.00	6.00	4.00	
VAR Sever	0.50	1.00	4.00	3.00	
Central Freq	0.17	0.25	1.00	0.33	
Central Sever	0.25	0.33	3.00	1.00	
Sum columns	1.92	3.58	14.00	8.33	
Normalize matrix (divide each entry by sum of associated column)					
Owner/Mgr Priorities	VAR Freq	VAR Sever	Central Freq	Central Sever	Avg (wt)
VAR Freq	0.52	0.56	0.43	0.48	0.50
VAR Sever	0.26	0.28	0.29	0.36	0.30
Central Freq	0.09	0.07	0.07	0.04	0.07
Central Sever	0.13	0.09	0.21	0.12	0.14

Figure 4.20: Criteria Weights

Step 2) Determine score for each of the alternatives.

In this step, the four trades (K, A, R, and HH) are compared to each other in each of the four categories. Saaty's rating scale is revised slightly to pertain more specifically to this case study, as shown in Table 4.9 below. The revised scale was based on my estimations of relative importance and could be adjusted to meet the specifics of other research as well.

Table 4.9: Revised Saaty Scale

Pairwise score	Comparison	Definition (using ratio of normalized values)
1	Equal	No statistical difference using ANOVA
2		1.01 to 1.16
3	Slightly favored	1.17 to 1.33 (one is about 25% higher than the other)
4		1.34 to 1.43
5	Strongly favored	1.44 to 1.56 (one is about 50% higher than the other)
6		1.57 to 1.66
7	Very strongly favored	1.67 to 1.83 (one is about 75% higher than the other)
8		1.83 to 1.99
9	Absolutely favored	> 2 (one is more than 2x higher than the other)

The ratio of the normalized values was used to determine which score to use from the revised Saaty Scale. The normalized values for each of the four categories were:

- Variation Frequency: Average percent of time a trade was associated with the top three causes of variation based on the number of tasks a trade performed.
- Variation Severity: Average magnitude associated with the top three causes of variation due to the trade in question.
- Centrality Frequency: Percent of the 14 areas in which the trade worked.
- Centrality Severity: Average degree centrality score for the trade.

Consider the comparison of trades K and A in terms of variation frequency (top line in upper left portion of Figure 4.21). The respective variation frequencies for trades K and A were 0.045 and 0.043. This indicates trade K is slightly more associated with the top three causes of variation than trade A. The revised Saaty Scale is used to determine a pairwise comparison score by using the ratio of the two (i.e. 0.045/0.043 = 1.05). In this case, 1.05 corresponds to score of 2 (i.e. between equal and somewhat more important). Pairwise comparisons were performed in a similar manner for the remainder of Figure 4.21.

Determine Scoring - Individual matrices											
	Pairwise Comparison					Normalized Matrices					
VAR Freq	K	A	R	HH		VAR Freq	K	A	R	HH	Avg (score)
K	1.00	**2.00**	0.20	0.11		K	0.06	0.11	0.05	0.07	0.07
A	**0.50**	1.00	0.17	0.11		A	0.03	0.06	0.04	0.07	0.05
R	**5.00**	6.00	1.00	0.33		R	0.32	0.33	0.23	0.21	0.27
HH	**9.00**	9.00	3.00	1.00		HH	0.58	0.50	0.69	0.64	0.60
	15.50	18.00	4.37	1.56							
VAR Sever	K	A	R	HH		VAR Sever	K	A	R	HH	Avg (score)
K	1.00	**2.00**	0.20	0.14		K	0.07	0.13	0.06	0.08	0.08
A	**0.50**	1.00	0.17	0.14		A	0.04	0.06	0.05	0.08	0.06
R	**5.00**	6.00	1.00	0.50		R	0.37	0.38	0.30	0.28	0.33
HH	**7.00**	7.00	2.00	1.00		HH	0.52	0.44	0.59	0.56	0.53
	13.50	16.00	3.37	1.79							
Central Freq	K	A	R	HH		Central Freq	K	A	R	HH	Avg (score)
K	1.00	**6.00**	8.00	5.00		K	0.67	0.57	0.57	0.75	0.64
A	**0.17**	1.00	2.00	0.33		A	0.11	0.10	0.14	0.05	0.10
R	**0.13**	0.50	1.00	0.33		R	0.08	0.05	0.07	0.05	0.06
HH	**0.20**	3.00	3.00	1.00		HH	0.13	0.29	0.21	0.15	0.20
	1.49	10.50	14.00	6.67							
Central Sever	K	A	R	HH		Central Sever	K	A	R	HH	Avg (score)
K	1.00	**0.50**	2.00	5.00		K	0.27	0.25	0.32	0.31	0.29
A	**2.00**	1.00	3.00	6.00		A	0.54	0.50	0.48	0.38	0.47
R	**0.50**	0.33	1.00	4.00		R	0.14	0.17	0.16	0.25	0.18
HH	**0.20**	0.17	0.25	1.00		HH	0.05	0.08	0.04	0.06	0.06
	3.70	2.00	6.25	16.00							

Figure 4.21: Scoring Results for Case Study

As with the criteria weights, the individual scoring matrices are normalized by the sums of the applicable columns. The rows of the normalized matrices are then averaged to determine the trade's "score" in terms of each of the four categories.

Step 3) Determine preferred alternative

In this example, the four trades (K, A, R, and HH) represent the alternatives as to which trade a project manger should focus on to reduce the top causes of variation. A summary of the overall AHP model is shown in Figure 4.22. In this case, trade HH (the steel fabricator/erector), is the top priority. The overall value for each alternative is determined by summing the products of the weights and scores for each alternative (Eq. 2).

$$Overall\ Value = \Sigma(Wt_i)(Score_i) \qquad \text{Eq. 2}$$

Example for trade K: Overall Value = (0.50)(0.07) + (0.30)(0.08) + (0.07)(0.64) + (0.14)(0.29) = 0.145 = 14.5%

Owner/Mgr Priorities	VAR Freq	VAR Sever	Central Freq	Central Sever
VAR Freq	1.00	2.00	6.00	4.00
VAR Sever	0.50	1.00	4.00	3.00
Central Freq	0.17	0.25	1.00	0.33
Central Sever	0.25	0.33	3.00	1.00
Sum columns	1.92	3.58	14.00	8.33

AHP Results	
K	**14.5%**
A	**11.4%**
R	**26.4%**
HH	**47.7%**

Normalize matrix (divide each entry by sum of associated column)

Owner/Mgr Priorities	VAR Freq	VAR Sever	Central Freq	Central Sever	Avg (wt)
VAR Freq	0.52	0.56	0.43	0.48	0.50
VAR Sever	0.26	0.28	0.29	0.36	0.30
Central Freq	0.09	0.07	0.07	0.04	0.07
Central Sever	0.13	0.09	0.21	0.12	0.14

λ_{max} =	4.115
CI =	0.038
CR =	0.043

Determine Scoring - Individual matrices

Pairwise Comparison

VAR Freq	K	A	R	HH
K	1.00	**2.00**	0.20	0.11
A	**0.50**	1.00	0.17	0.11
R	**5.00**	6.00	1.00	0.33
HH	**9.00**	9.00	3.00	1.00
	15.50	18.00	4.37	1.56

VAR Sever	K	A	R	HH
K	1.00	**2.00**	0.20	0.14
A	**0.50**	1.00	0.17	0.14
R	**5.00**	6.00	1.00	0.50
HH	**7.00**	7.00	2.00	1.00
	13.50	16.00	3.37	1.79

Central Freq	K	A	R	HH
K	1.00	**6.00**	8.00	5.00
A	**0.17**	1.00	2.00	0.33
R	**0.13**	0.50	1.00	0.33
HH	**0.20**	3.00	3.00	1.00
	1.49	10.50	14.00	6.67

Central Sever	K	A	R	HH
K	1.00	**0.50**	2.00	5.00
A	**2.00**	1.00	3.00	6.00
R	**0.50**	0.33	1.00	4.00
HH	**0.20**	0.17	0.25	1.00
	3.70	2.00	6.25	16.00

Normalized Matrices

VAR Freq	K	A	R	HH	Avg (score)
K	0.06	0.11	0.05	0.07	0.07
A	0.03	0.06	0.04	0.07	0.05
R	0.32	0.33	0.23	0.21	0.27
HH	0.58	0.50	0.69	0.64	0.60

VAR Sever	K	A	R	HH	Avg (score)
K	0.07	0.13	0.06	0.08	0.08
A	0.04	0.06	0.05	0.08	0.06
R	0.37	0.38	0.30	0.28	0.33
HH	0.52	0.44	0.59	0.56	0.53

Central Freq	K	A	R	HH	Avg (score)
K	0.67	0.57	0.57	0.75	0.64
A	0.11	0.10	0.14	0.05	0.10
R	0.08	0.05	0.07	0.05	0.06
HH	0.13	0.29	0.21	0.15	0.20

Central Sever	K	A	R	HH	Avg (score)
K	0.27	0.25	0.32	0.31	0.29
A	0.54	0.50	0.48	0.38	0.47
R	0.14	0.17	0.16	0.25	0.18
HH	0.05	0.08	0.04	0.06	0.06

Figure 4.22: AHP Summary for Prioritizing Trades K, A, R, and HH to Variation Reduction

Step 4) Calculate consistency ratio (CR).

Inconsistency in pairwise comparisons may be as a result of (1) inadequate knowledge, (2) improper conceptualization of hierarchy, or (3) lack of statistically power due to sample size. A CR is generated for each prioritized scale upon completion of carrying out the pairwise comparison. The CR is used to determine the consistency of the judgments. The CR is defined as the consistency index for a particular set of judgments divided by the average random index. The CR measures how consistent the judgments pertaining to the pairwise comparisons were. The intent is to not force the consistency. For example if B is favored over A by 2:1 and C is favored over B by 3:1, it is not required that C be favored over A by 6:1. On the other hand, A would not be expected to be favored over C given the first two conditions. The CR will identify inconsistencies such as this in the pairwise comparisons. An acceptable CR is $\leq$ 0.10 or 10% (Saaty, 1980). The steps for calculating the CR along with an example using the case study are shown below:

$CR = CI / RI$, where: Eq. 3

CI = Consistency Index = $(\lambda_{max} - n) / (n-1)$, where: Eq. 4

λ_{max} = maximum eigenvalues = Σ(Column sums)(Row Weights) Eq. 5

n = number of items (rows or columns) in the comparison matrix

RI = randomly generated CI and is determined from Table 4.10.

Table 4.10: RI Values for Calculating the CR

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.59

The CR for the case study is calculated using the values in Figure 4.22.

λ_{max} = 1.92(0.50) + 3.58(0.30) + 14.00(0.07) +8.33(0.14) = 4.115

CI = (4.115 – 4) / (4 – 1) = 0.038

$CR = CI/RI$ (*from* Table 4.10) = 0.038 / 0.9 = 0.043 (<0.10 = acceptable)

If the CR had been greater than 10%, the pairwise comparisons would have needed to be relooked to ensure there was not a logical error in the comparisons.

4.2.3 Case Study 1 Discussion and Conclusions

Initially, the GC intended to use the Last Planner System (LPS) ® to manage their weekly planning meetings (Ballard, 2000). The actual planning process encompassed some of the framework of the LPS®, but not all of it. For example, they reviewed the previous weeks' work and used a look-ahead process; however, the look-aheads were not conducted as intended by the LPS®. One of the key purposes of the look-ahead is to identify and remove constraints, which are items that need to be completed and/or addressed prior to a task being started (Ballard 1997). Once the constraints for a task have been removed, the task is "made ready" and the commitment to accomplish the task is more reliable (González et al. 2010). Look-aheads are an important aspect of the LPS® and Alarcón et al. (2005) found that PPC improved when companies included the use of look-aheads while implementing the LPS®. The project manager involved with this case study stated they did not work to identify and remove constraints to the extent they had envisioned during their look-aheads. The project manager plans to use the results of this study in a future project, which uses many of the same trades and involves a similar scope of work. He feels the insight provided by the social network coupled with the variation analysis, along with a more thorough look-ahead process in their weekly LPS® meeting, will results in a more efficiently executed project.

The frequency – severity characteristic associated with risk assessment matrices was used to examine approximately 1200 tasks performed by 43 different trades and identify the top three causes of variation. Material delivery and not having prerequisite work completed were the top two causes of starting time variation and overcomittement was the top cause of task duration variation. Pajek was used to identify a social network of trades for each of the 14 areas associated with the project in this study. Eigenvector and degree centrality analysis identified the key trades within the networks. Lastly, the results of the variation analysis and that of the social network analysis were combined to identify and prioritize the trades, in terms of their associated relative variation and how central they were to the overall project. The mechanical and electrical contractors were identified as the top two trades overall. The painting contractor was next in priority, followed by a group of four trades that were considered to be relatively equal in priority. Those four trades represented the drywall, ceiling, flooring, and steel fabricator/erector contractors. The Analytical Heierachy Process was used as a decision support tool to prioritize those four trades. The results of the AHP analysis indicated the steel contractor should be the top priority among those four trades, followed by flooring, drywall, and then the ceiling contractor. The project manager involved with the case study intends to use the results of this study to reduce variation on an upcoming project by focusing on these specific trades and causes of variation during their weekly LPS® meetings.

4.3 Case Study 2

4.3.1 Case Study 2 Results

Recall, this case study involved a mechanical contractor executing and comparing two similar projects. One of them used the LPS® system and the other did not. Both projects were studied from the start of June through the end of September in 2010. Initially, the results of the variation survey served as a guide to determine the focus areas for anticipating the causes of variation. Since the study focused on the mechanical contractor, the concept map (Figure 4.6) suggested to focus primarily on the labor force, equipment coordination and management, tools and personal protective equipment, and material management. As the study progressed, and the company started creating their own database of causes of variation, they were able to adjust the planning focus as they saw fit. Data was collected from the beginning of June through the end of September 2010 for each project in order to address each of the research objectives.

4.3.2 Case Study 2 Analysis

Objective 3: Determine the causes of variation that pose the greatest risk of impacting project performance.

Two different plots were used to address this research objective. First, a Pareto chart depicting the frequency for different causes of variation was used (Figure 4.23).

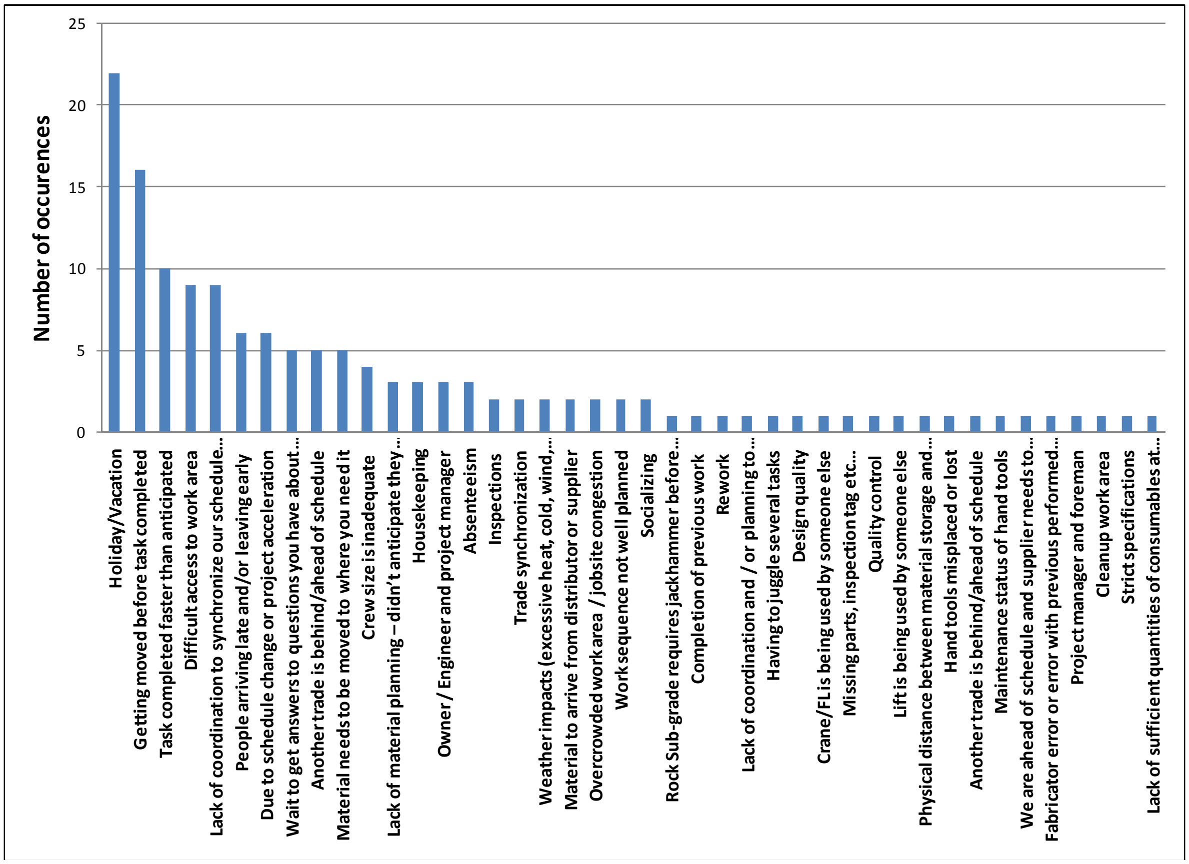


Figure 4.23: Pareto Chart of Causes of Variation

The Pareto chart alone doesn't adequately depict which causes of variation pose the greatest risk as it only captures the frequency. Risk is composed of frequency and severity. Recall from Figure 1.1, items that have a high frequency and high severity (i.e. fall in the upper right corner of the matrix) pose the greatest risk. Figure 4.24 uses the risk assessment matrix to illustrate the causes of variation over the 16 weeks for the LPS® project.

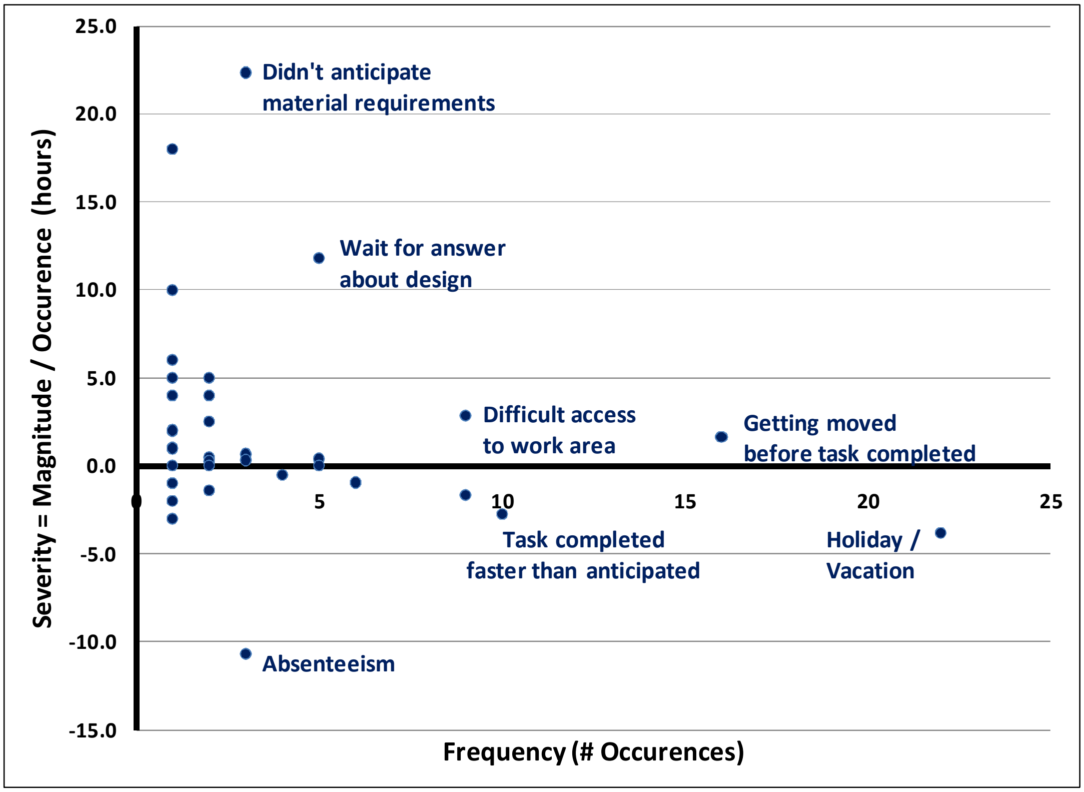


Figure 4.24: Causes of Variation for 16 Week LPS® Project

The two causes of variation that posed the greatest risk to the project performance in terms of productivity for the mechanical contractor were "not anticipating material requirements" and "waiting for answers to questions about the design." It is important to note that this would not be apparent when relying solely on the Pareto chart, as these two items ranked 12th and 8th respectively in terms of just their frequency. Although the frequency was lower than two other causes (i.e. "difficult access to the work area" and "getting moved before the task was complete"), the severity was greater. This shows were there can be some subjectivity in the decision as to which poses the greatest risk because there is a trade-off between severity and frequency. It should also be noted that if all causes of variation that were deemed to be feasible for reduction and/or elimination could be targeted simultaneously, there would be no need for risk assessment. However, this assumes unlimited capacity for variation reduction and this may not always be feasible. Therefore, risk assessment is justifiable when there is limited capacity for action and hence a need to prioritize the use of that capacity.

The risk assessment matrix illustrates the magnitude of variation, whether positive or negative. Ideally, there is no variation and planned and executed activity durations are identical. It is relatively obvious that when the actual duration is longer than the planned duration, a delay occurs and those situations to avoid. However, when the actual duration is shorter than the planned, this is an opportunity to possibly exploit. Regardless, it is essential that the causes of variation are diagnosed in order for them to be dealt with. Conducting a 5-why analysis is a potential means to determine the root reason for the occurrence of variation. The 5-why analysis is part of the Toyota Production System (Ohno 1988) and involves repeating why multiple times to help identify the nature of a problem as well as its solution. The "Five Whys" comes from the observation that an actionable cause is usually identified by or before the fifth time "why" is asked. The people involved with this type of analysis need to be capable of answering those questions.

In some instances, it may not be so much a matter of limited capacity for problem solving, as a matter of having an appropriate plan for problem solving. Some learning will take place at the level of the last planners themselves; e.g., 'remember to adjust capacity assumptions for holidays and vacations.' Some learning will take place within the project, but require multiple players to adjust their shared process; e.g., allocating shared resources such as cranes and elevators. Some learning will require collaboration with players outside the project site; e.g., pull planning with designers to design a process for work packaging and delivery of design. Yet other problems may require policy changes at the corporate level of the mechanical contractor or their suppliers or customers.

Objective 8: Compare performance in terms of productivity and cost savings for two similar projects, in which the LPS® was used on one, but not the other.

The first step in analyzing this research objective was to determine if using the LPS® would reduce variation. In order to determine this, the data from the study was split in half to see if there was a difference in variation as the project progressed. The magnitude and reason for variation was tracked for each task on the weekly work plan for the LPS® project. The non-LPS® project did not track variation. The company used the 50 causes identified by Wambeke et al. (2011) as the baseline for their reasons of variation. Those 50 causes were typically associated with variation causing a delay. The company added additional reasons for variation as required, particularly for variation in which less time was spent on a task than was planned. Figure 4.25 and Figure 4.26 illustrate the causes of variation for the first and second halves of the LPS® project. Each dot in the matrices represents a reason of variation. The horizontal axis is the frequency, or number of times, a particular reason of variation occurred. The vertical axis is the mean magnitude normalized by the number of occurrences for each reason. It is clear from these figures that project managers, superintendents, and foremen are faced with numerous causes of variation. The risk assessment matrix enables managers to prioritize those causes of variation based on their frequency and severity. There were five causes of variation that will be discussed that occurred during the first half of the study. There were two instances in which material was not available due to a lack of planning, which was consistent with the concept map (Figure 4.6). The lack of anticipating material requirements resulted in an average variation of 34 labor hours each time it occurred. The next cause of variation to highlight was the site conditions. During excavation procedures, the company experienced more rock than anticipated and spent an additional 18 labor hours as a result. The third cause of variation to point out is "difficult access to the work area." Although the severity was relatively low (3.2 labor hours/occurrence), this was the item that most frequently caused a task to take longer than planned.

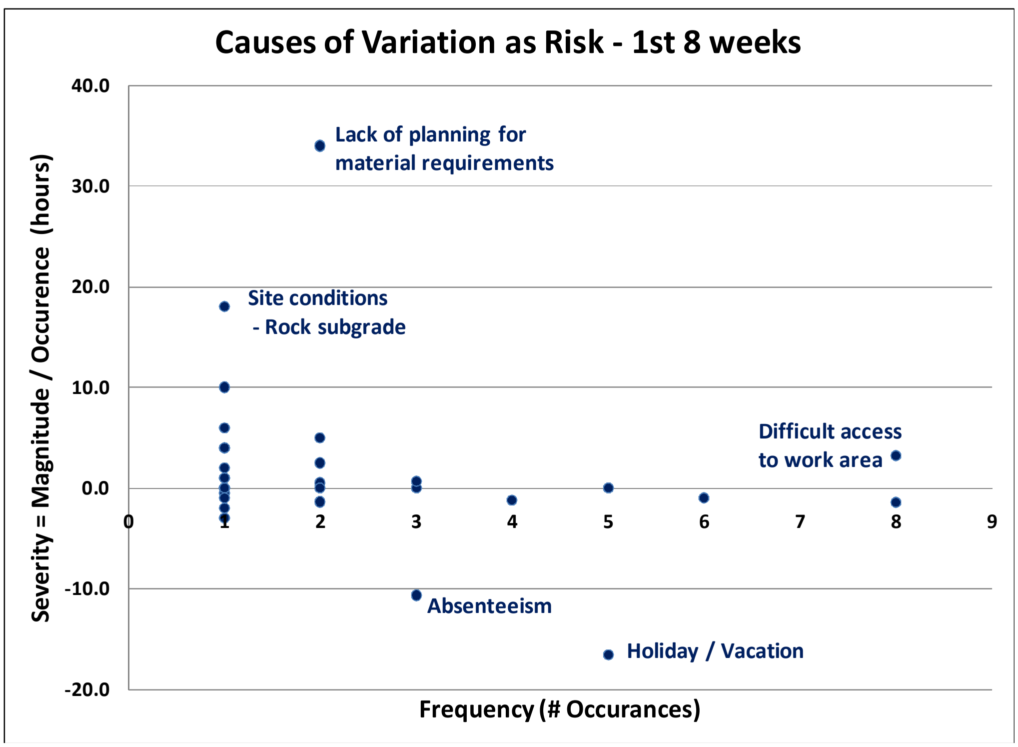


Figure 4.25: Frequency and Severity of Variation for the 1st Half of the LPS® Project

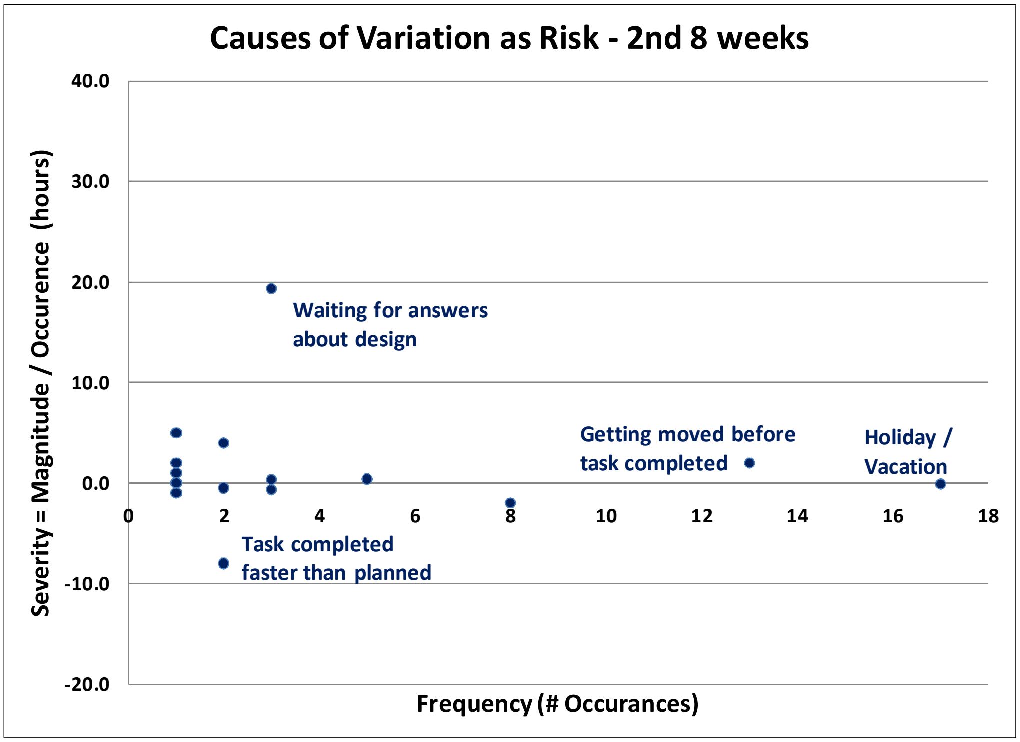


Figure 4.26: Frequency and Severity of Variation for the 2nd Half of the LPS® Project

There were two causes of negative variation (i.e. less time was spent on a task than was planned) to highlight. Only tasks that were completed were included in Figure 4.25 and Figure 4.26 where negative variation was concerned. For example, if 50 less labor hours were spent on a task than were planned, but the task was not completed, that particular instance of negative variation was not included in either of those figures. Absenteeism occurred three times with an associated variation of slightly less than -10 labor hours. This indicates someone either didn't show up for work or called in sick and the crew worked short-handed, but still completed the task. The other cause of negative variation to highlight revolved around the 4th of July holiday. Crews worked at a faster rate than normal in order to get off early prior to the long weekend. Although they worked faster, they still completed their tasks to standard, thus those items were included in Figure 4.25. The "lack of planning for material requirements" was consistent with the concept map in Figure 4.6, as were the "absenteeism" and "holiday/vacation" as they both pertained to the labor force. The project manager, superintendent, and foreman used the risk assessment matrix in conjunction with their weekly Last Planner® meetings to identify and prioritize which causes of variation should be targeted for reduction. Their top concern was the lack of planning for materials, followed by creating easier access to the work area. There was no action taken to remedy the unforeseen subsurface conditions as that portion of the project had been completed by this point.

The second half of the project is depicted in Figure 4.26. The vertical axes of both matrices were kept the same to illustrate there is a reduction in the normalized magnitude of variation in the second half of the project. There were no more instances in which a lack of planning for materials, which was the greatest concern during the first half of the project, caused variation. Additionally, the difficult access due to site conditions was no longer a cause of variation. It is not known whether this was due to the evolving construction site or whether it was due to actions taken by the employees. There were three instances in which the company had to wait on answers pertaining to the design. Each of these cases resulted in a variation of about 20 labor hours. This is consistent with Dia et al. (2009) as they found this to be one of the top factors that affect productivity. This cause falls under the "senior management coordination" factor in the concept map (Figure 4.6) and demonstrates that although this factor is more likely to be associated with a company dealing with multiple trades; it should not be ignored by a company working with a few trades. The other point to illustrate is that this company used a 3 week look-ahead, rather than the 6 week look-ahead recommended by Ballard with the LPS® (Ballard, 2000). Information about when the questions pertaining to the design were posed was not captured; therefore, it cannot determined if the 3 week look-ahead was adequate or it the look-ahead needed to be longer. Labor Day weekend again caused a high frequency of variation, but the overall magnitude was about zero, which indicated the foreman anticipated the holiday weekend and adjusted the work load on the weekly work plan so there was no a large variation. The other two items indicate crews were completing tasks faster than planned. There were 13 instances in which a crew (or part of a crew) was moved to another task prior to completing with the task they were currently working on was complete. This had a corresponding normalized magnitude of 2.0 labor hours and was the decision of the foreman based on progress made by the crews. He chose to spend more labor hours than planned in order to begin work on other tasks. The last item to highlight was the two instances in which a task was completed faster than planned, which resulted in a variation of -8.0 labor hours per occurrence.

Even though this was the company's first attempt at using the LPS®, the foreman, superintendent, and project manager felt the LPS® reduced variation and improved the reliability of the weekly work plan. This is important as variation in completing planned tasks can affect downstream trades as well as the performer—in this case, the mechanical contractor. Although other trades were not included in this study, downstream trades are still an important consideration. Impact on the performer may be small in terms of labor hours lost, but the productivity impact on downstream trades may be larger, if they are unable to perform a planned task because its predecessor was not completed by the performer. There is also the potential impact on project progress. If tasks are critical, failure to complete them on time either extends the project or necessitates replanning to find an alternative critical path or a means for accelerating along the original critical path.

The project manager felt their use of the LPS® will continue to improve as using it can presumably prevent potential variation by:

- focusing on the removal of constraints during the planning and preparation.
- following the rule to include on weekly and daily work plans only tasks that have had all constraints removed beforehand that can be removed beforehand, and by careful assessment of the probability that remaining constraints will be removed in time, plus perhaps proactive steps taken to improve those probabilities.
- requiring specific attention to matching capacity to load, so that there is sufficient capacity to perform weekly work plan tasks.
- analyzing experienced variation to root causes and acting on those causes.

The company's traditional planning system did not track variation, but did track productivity for the primary activities associated with the project. These activities are shown on the horizontal axis in Figure 4.27. The first four activities, since they are abbreviated in Figure 4.27, are spelled out for clarification. They are piping and fitting for under ground cast iron, above ground cast iron, steel, and copper. There were three activities (fixtures, commissioning, and shop) that had not been performed at the conclusion of the study; therefore, they do not have a bar associated with them in Figure 4.27. The activities were still listed so readers would not be confused as to why these common tasks were not included. The vertical axis of Figure 4.27 is the performance index the company uses to measure its productivity. It is the ratio of earned to spent man-days for each activity. Ideally, this index is greater than or equal to 1.0. If the ratio is greater than 1.0, this indicates that more man-days were earned (i.e. the company was paid for) than were spent, on a particular activity. In all but one activity (installing equipment), the LPS® project outperformed the non-LPS® project. The reason for a lower productivity with this activity was not ascertained in the study. In terms of overall performance, the LPS® project had about a 35% higher productivity perfomance index (1.03) than the non-LPS® project (0.76). Given the low performance index of the non-LPS® project, it could be argued that it was not representative of the company’s capability. The company involved with the case study has a solid reputation and history as a company that performs very well. Based on discussions with the president of the company and the project manager, they felt even though the non-LPS® project's performance index was lower than desired, it was still appropriate to compare the performance of the two projects because of the similarities in the scopes of work.

The company estimated they spent about an additional $4000 in planning costs over the 16 months for the LPS® project. These costs were due to having an extra project manager coordinate and run the weekly LPS® meetings. Access to the specific total planning costs for each project was not provided; therefore, just the estimated additional costs due to implementing the LPS® were included. The estimated savings for the LPS® project were approximately $52,000, thus resulting in a benefit / cost ratio of 13:1.

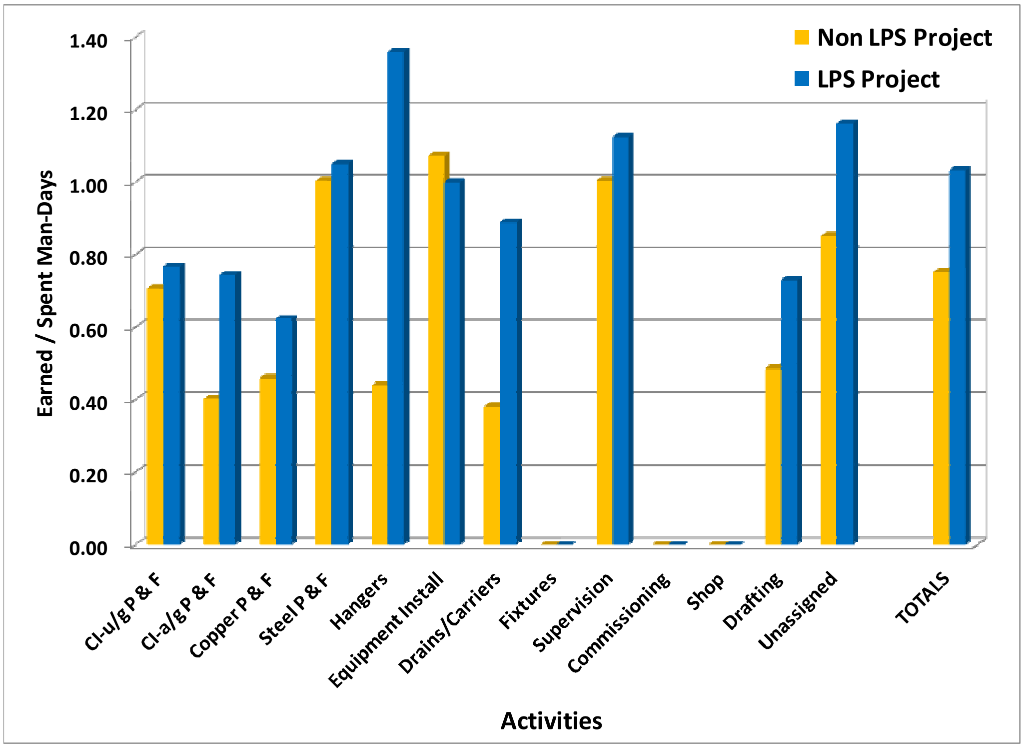


Figure 4.27: Project Productivity Performance for LPS® and non-LPS® Projects

4.3.3 Case Study 2 Discussion and Conclusions:

This study also provided quantitative data that demonstrated how using the LPS® reduced and/or eliminated variation for the mechanical contractor involved with this case study. The research also demonstrated again how a risk assessment matrix can be used to analyze and prioritize variation so it can be attacked. The risk assessment matrix is valuable because it considers both frequency and severity and is justified when there are limited capabilities to simultaneously affect multiple causes of variation. The Pareto chart analysis demonstrated that the most frequent causes are not always the most critical ones. Using the LPS® not only reduced variation during the execution of the LPS® project, it resulted in a

35% higher productivity performance and benefit / cost ration of 13:1 over the non-LPS® project. Although the findings of this study are based on a mechanical contractor, this research can have a broader impact on the construction industry as the methods described in this study can be applied to other trades as well. This research provides an example of how project and field managers can combine the use of the LPS® and a risk assessment matrix in their efforts to prioritize and reduce variation to improve project performance. The president of the company involved in this study was encouraged by the results of this research and is moving ahead to implement similar techniques throughout the remainder of the company.

4.4 Case Study 3 (Masonry Restoration Companies)

4.4.1 Case Study 3 Results

As discussed in Chapter 3, this case study did not take place as planned. One of the companies (MR2) decided not to provide any data related to their project. A site visit to MR2's project was conducted, therefore the observations as they relate to this research are discussed.

The project manager and foreman for MR1's project met weekly to conduct a Last Planner® meeting. During the first two or three meetings, they included the facilities manager from the apartment complex to ensure their work plan was acceptable and did not interfere unnecessarily with the occupants of the building. The LPS® meetings lasted approximately 45 minutes to 1 hour and through the use of the meetings, both the project manager and foreman felt they effectively removed constraints to create a reliable schedule. Figure 4.28 depicts the starting time and task duration variation, as well as the PPC for MR1's project. There were two days of starting time variation at the beginning of the project because an air compressor did not work and a part needed to be replaced. There was one other instance of starting time variation. In week 4, the construction manager from their main office changed priorities and asked that the crew participate in companywide safety training. There are four instances of task duration variation, two are positive and two are negative. In both instances, the crew completed the work faster than originally estimated; therefore, scheduled tasks were altered (i.e. the crewed performed demolition instead of repair). Due to the low amount of variation, and the fact that there was no variation data from MR2 to compare it to, it was not plotted in a risk assessment matrix format.

	10-Apr Wk 1	17-Apr Wk 2	24-Apr Wk 3	1-May Wk 4	8-May Wk 5	15-May Wk 6	22-May Wk 7	29-May Wk 8	5-Jun Wk 9
Starting Time Variation (days)	2			1					
Reason	Equipment maintenance			FM change priority					
Duration Variation (days)		-1	1		1	-1			
Reason		Task complete early	Repair instead of demo		Demo instead of repair	Repairs complete			
PPC	71	83	90	91	93	90	100	100	100

Figure 4.28: Variation and PPC Data from MR1's Project

The site visit of MR2's project was conducted on one and communication with the project manager was performed on several occasions via telephone and email. Although the company did not provide any data, the project experienced two significant causes of variation. First, MR2 did not synchronize their work plans with the owners/occupants of the building. The project manager recalled at least four instances when they were not allowed to conduct the work they had planned for the day. These instances were due to meetings or other activities the owner/occupants were conducting in a portion of the building near where the crew from MR2 was working. The nature of the work (i.e. a suspended scaffold) precluded the crew from just working on another face of the building. It takes the majority of a day for the crew to move the rigging and scaffolding; therefore, it was not practical to do so before the face of building they were working on was complete. The other major cause of variation had to do with how the engineer wanted the crews to perform the work and based on the owner/occupant's acceptable noise levels. Cutting out the old pointing involves removing the mortar from between the bricks to a specified depth (5/8" in this case). This is typically done with a handheld rotary grinding tool with a masonry cutting disk. The horizontal cuts are made first and then the vertical cuts. There is a small piece of mortar that cannot be cut with the rotary disk on the top and bottom of the vertical cuts without cutting into the brick directly above or below the vertical cut. Figure 4.29 depicts where this piece of mortar is located. The right side of the diagram is looking at the end view of the vertical cut between bricks A and C and along the side face of brick B.

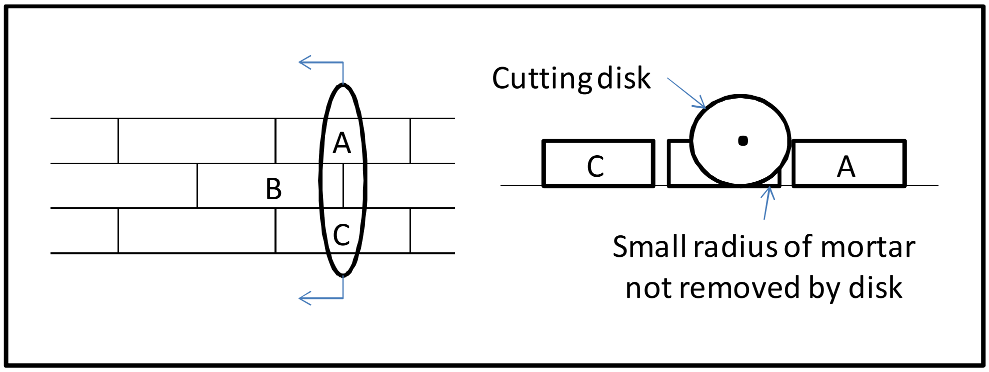


Figure 4.29: Diagram of Vertical Cut for Removing Old Pointing

MR2's standard practice was to use a small handheld impact tool that works much like a small jackhammer to chisel this piece of mortar out. However, the owner/occupant said the impact tool created excessive and unacceptable noise levels; therefore, the workers had to chisel each of these pieces out by hand. The project manager estimated this would have added a minimum of two weeks to the overall schedule; however, the crews planned to work overtime because the owner would not change the required project completion date.

4.4.2 <u>Case Study 3 Analysis</u>

Since data was not available from both companies, no analysis was performed for this case study.

4.4.3 Case Study 3 Discussion and Conclusions

Although this case study did not provide an opportunity to compare the performance of the two companies in a similar fashion as the two projects were compared with the previous case study, there are some key points of discussion. The first has to do with the coordination that took place between each of the companies and the owner/occupants of the buildings. MR1 included the facilities manager in their LP® meetings to ensure MR1's work schedule and techniques were acceptable to the owner/occupants. It is not known if MR1 adjusted any of their planned work based on the owner/occupant's requests, but there were no reported instances in which work was interrupted due to an issue from the owner/occupant. This is not the case with MR2, as they had issues with both synchronizing work schedules and with the work method. This illustrates the importance of identifying and removing potential constraints during a weekly planning meeting, or at some point prior to the work beginning.

The second point of discussion deals solely with MR1. The company uses on time delivery (OTD) as a metric to gauge the performance of the company. OTD is simply the percentage of work that is completed by the time it was planned to be completed. The goal is to achieve $\geq$ 100% OTD. An OTD < 100% indicates the work is/was behind schedule. MR1 was struggling with poor performance in the mid to late 2000s. In 2008, the company's average OTD was 62% and the company was close to going out of business according to the company's president. Although they didn't track variation, he said it was rampant in almost every project. In the spring of 2009, the president of the company decided to learn about and implement some Lean Construction practices. He began by standardizing their warehouse and job trailers because one of the largest causes of variation was not having the proper tools or equipment or not being able to find them. They also inventoried, organized, and labeled all of the various materials they use on a regular basis as this was another cause of variation for them. The other major change they made as a company was to implement the use of pull-planning sessions and Last Planner® meetings in accordance with the LPS® (Ballard 2003). As a result of these changes, the company's performance improved dramatically as can be seen in Figure 4.30. The company's average OTD increased from 62 % in 2008 to just over 100% in 2009. Each point in Figure 4.30 represents the OTD from a separate project. These results illustrate the impacts proper planning can have to identify and reduce variation and improve project performance.

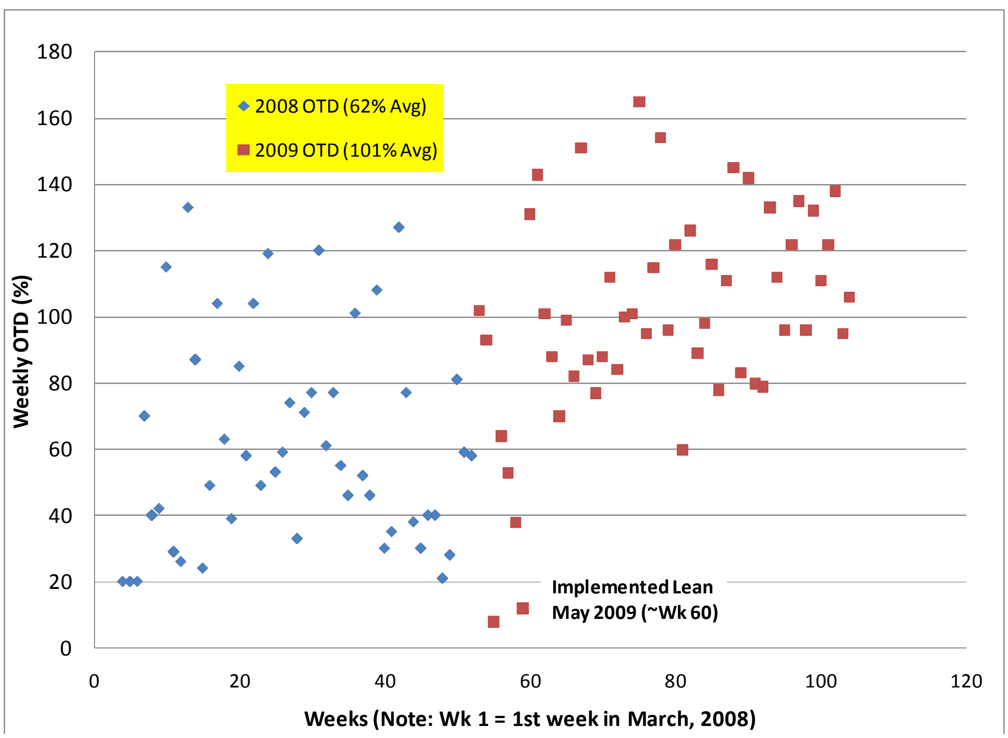


Figure 4.30: MR1 OTD – Before and After Implementation of LPS® and Lean Construction Practices

CHAPTER 5

5.0 SUMMARY AND CONCLUSIONS

Identifying, prioritizing, and reducing the variation of construction related tasks doesn't typically happen by chance; rather it requires planning. It takes the right people, talking about the right things, at the right time. This research provides the frame work to do just that and is summarized in the following sections.

5.1 Existing Gaps in the Body of Knowledge

Several researchers identified various items that impacted productivity. While an assumption could be made that many of these same items would also be the same items to cause variation, no research was specifically conducted to do so. This was the first gap in the body of knowledge pertaining to this research.

There are two overarching views pertaining to variation. One view is that it is feasible and important to first reduce variability to the extent possible, and then buffer what cannot yet be eliminated. The opposing view focuses on buffering first, rather than reducing the causes of variation by some form of management action prior to buffering. Adherents from both views would agree that variation is prevalent in the construction industry and if provisions are not made to deal with it, variation can have detrimental impacts on productivity. Despite the importance, little research has been performed to quantify the amount of variation that occurs due to various different causes. When combined with the first gap in the body of knowledge, a need to identify and quantify the most prevalent causes of variation was discovered. This served as the initial motivation for this research.

As the research progressed, other gaps were discovered as well. Some researchers grouped the items impacting productivity together using techniques such as factor analysis, while others rank ordered them based on their frequency of occurrence. No research was performed to prioritize which causes posed the greatest risk to project performance based on their frequency and severity; thus another gap was identified. If a project manager has limited capabilities to simultaneously affect all of the causes of variation, how should he/she prioritize which ones they should focus on?

Understanding what the causes of variation are is part of the solution in the effort to reduce the variation. It is also important to know who is causing the variation and/or who is being impacted by it. This can be difficult as construction projects often consist of a complex series of interdependent tasks and trades that a project manager works to synchronize to the best of his/her ability. Plausibly and arguably, there is an underlying social network of trades that exists and recognizing it can help to understand how the variation impacts the overall project. Research has been conducted to identify the social networks based on communication between members of construction project management teams; however, no research pertaining to the social network of trades was identified in academic research. The use of social networks, particularly as they are related to the various trades of a project, was another gap in the body of knowledge.

Lastly, there has been no empirical research conducted that quantifies the cost savings based on improved productivity due to a focused planning effort to target and reduce variation.

5.2 Review of Research Objectives

The gaps in the body of knowledge drove the research objectives. Imagine the body of knowledge pertaining to variation as a vast plain of information, with a hole in the surface being the top of a funnel that represents the gaps in the body of knowledge pertaining to this research (Figure 5.1). The top of the funnel is wider and is associated with a broader aspect of the research. The deeper one goes into the funnel, the more specific and directed the research tends to become. The gaps in the body of knowledge are listed along the left side of Figure 5.1, while the associated research objectives are listed along the right.

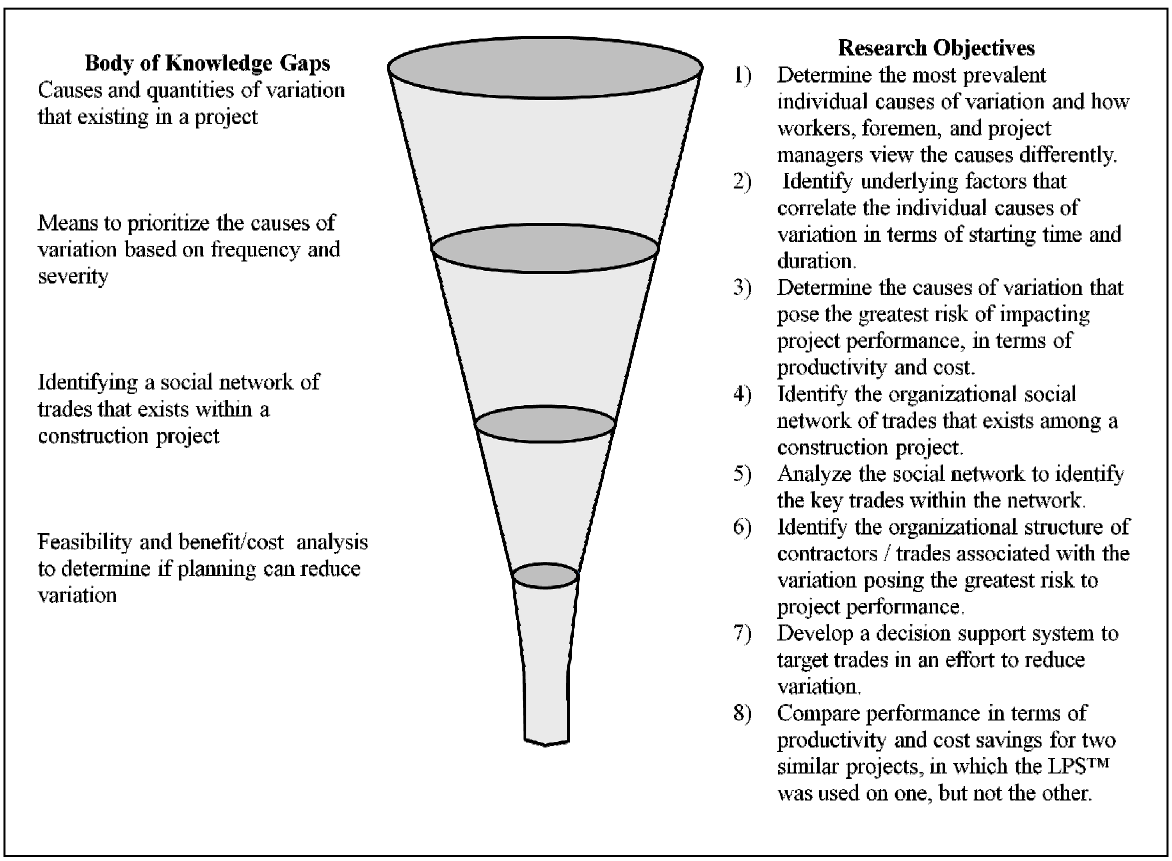
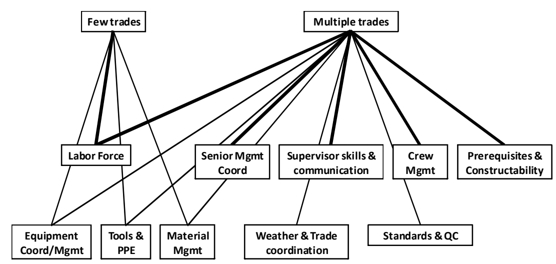


Figure 5.1: Summary of Gaps in the Body of Knowledge and Research Objectives

5.3 Research Summary

A summary of the research objectives, associated methodology and conclusions/key findings was created to highlight the major aspects of this research (Table 5.1).

Table 5.1: Summary of Research Objectives, Methods, and Conclusions

Research OBJs	Research / Analysis Method	Conclusions / Key Findings
1) Determine the most prevalent individual causes of variation and how workers, foremen, and project managers view the causes differently.	Created and distributed a survey to collect data about most prevalent causes of variation (124 useable responses). Cross referenced repsonses of workers, foremen, and project managers to identify top causes of variation as well as differences in perspectives.	Top 10 overall individual causes of variation: 1. Turnaround time / waiting to get answers when there is a question with a drawing 2. Completion of previous work (i.e. work before you isn't done yet) 3. Obtaining required permits for the work to begin 4. Socializing (talking with fellow workers) 5. Quality of documents (errors in design and/or drawings) 6. Rework being required due to the quality of previous work 7. Weather impacts (excessive heat, cold, wind, rain, etc.) 8. Worker/crew lack of skills/experience to perform the task(s) being asked of them 9. People arriving late and/or leaving early due to illness, injury, personal reason, etc. 10. Need guidance or instruction from supervisor
2) Identify underlying factors that correlate the individual causes of variation in terms of starting time and duration.	Used factor analysis to identify underlying factors that correlated the individual causes of variation. Developed a concept map based on factor analysis results and the number of trades involved.	
3) Determine the causes of variation that pose the greatest risk of impacting project performance, in terms of productivity and cost.	Case Study used to collect data - GC with 43 trades construction $50M data center over 28 week period	Top three causes of variation: 1) Material delivery issues 2) Prerequisite work not completed 3) Over commitment
4) Develop the organizational social network of trades that exists among a construction project.	Used risk assessment matrix to determine causes of variation posing greatest risk to project performance.	14 social networks identified based on work break down struction of project.
5) Analyze the social network to identify the key trades within the network.	Pajek was used to identify social networks of trades.	
6) Identify the organizational structure of contractors / trades associated with the variation posing the greatest risk to project performance.	Conducted degree and eigenvector based centrality analysis to ID key trades.	Results of combining variation and SNA/centrality analysis to determine trades to focus on for variation reduction by project manager: - Mechanical and electrical subcontractors were identified as the top two trades overall - Painting contractor was next in priority - Group of four trades (drywall, ceiling, flooring, and steel fabricator/erector) were 3rd priority
7) Develop a decision support system to target trades in an effort to reduce variation.	Combined variation and social network/key trade analysis to develop decision support system to target variation for reduction. Used AHP to support decision making when multiple criteria involved with the decision.	
3) Determine the causes of variation that pose the greatest risk of impacting project performance, in terms of productivity and cost.	Case study involving a mechanical contractor conducting two similar projects. One project used Last Planner System® along with a risk assessment matrix to identify and prioritize variation for reduction. The other project did not use LPS®.	Top two causes of variation that posed the greatest risk to the project performance in terms of productivity: 1) Not anticipating material requirements 2) Waiting for answers to questions about the design
8) Compare performance in terms of productivity and cost savings for two similar projects, in which the LPS® was used on one, but not the other.	Used benefit cost ration and end of project productivity results to compare the two projects	Variation in the LPS® project decreased between first 8 weeks and the 2nd 8 weeks. Productivity was 35% higher for the LPS® project with a 13:1 savings benefit/planning cost ratio

5.4 Conclusions

The intellectual merit associated with this research results from the contributions to the body of knowledge related to variation within construction projects, as well as the broader impact it has on the construction industry and beyond. This research:

- identified and quantified the most prevalent causes of variation associated with construction projects 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 database, created from vast project locations and trade networks, where complex, fault-tolerant, and lean performance must be achieved through the cooperation and coordination of those involved.
- provided a means to prioritize which causes of variation posed the greatest risk to project performance based on their frequency and severity;
- was the first of its kind with regard to using social network analysis to examine the network of trades and identify those trades that were key members of the network. Thus, it will provide a deeper understanding of the relationship between project decision factors and the social network of tradesmen, which will advance understanding in both engineering and human factors.
- has provided a fundamental understanding of the interdependency among trade networks, and provides insights into the capabilities and limitations of the hierarchical relationship in construction planning.

- has a broad application, from distributed networks to large operation scheduling and coordination (e.g., military logistics, global supply chains) where global-to-local optimal planning (for cost, schedule, and productivity) and scalable fault-tolerant control remain significant challenges.
- 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 complex functional global objectives, through AHP, can be translated into local plans of actions and interactions in such a large-scale construction project.
- provides empirical results quantifying the cost savings based on improved productivity due to a focused planning effort to target and reduce variation using the LPS®.
- provides the framework and repeatable analytical methods to identify, prioritize, and reduce variation on a construction project.

The two companies involved with the research are both using the results of the case studies and this research to implement changes within their companies as they strive for continuous improvement, which I feel is a testament to the value of this research. Personally, that is very rewarding as I had two primary goals when starting this research. First, I wanted to make a contribution to the academic body of knowledge worthy of a PhD. Second, I wanted the research to be useful for practicing members of the construction industry.

5.5 Recommended Future Research

While this research possessed both breadth and depth, there are additional closely related areas that warrant future research. Four such areas are recommended below:

1. This research examined and found using the LPS® was effective in reducing variation and improving craft productivity. The LPS® was designed to improve both craft productivity and project progress; however, the latter was not studied as part of this research. Therefore, one aspect of recommended future research is to perform case studies to determine the impact of reducing variation has on project progress.
2. One of the case studies in this research involved a general contractor with multiple subcontractors and the other involved only a mechanical contractor. As discussed, a third case study was planned between separate two companies. This would have added more breadth to this research, but one of the companies decided to not participate after initially agreeing to do so. It is recommended additional case studies, with various other trades and/or with different companies, be conducted to further validate or challenge the results of this research.
3. This research exposed the use of social network analysis to trades of a construction project; however, more research can be done in this area. One example would be to divide the social network into groups based and then conduct factor analysis on each group to determine if the subgroups were associated with different underlying factors. This research might be of value in determining if different decision making strategies are warranted for different subgroups of a social network. Another example would be to incorporate the use of hierarchical clustering in addition to the key trade identification

and analysis. Lastly, K-L Divergence could be used in conjunction with the social network analysis.

4. Proponents of Lean Construction feel is it feasible and important to first reduce variation to the extent possible, and then buffer what cannot be eliminated. This research demonstrated it is feasible to identify, prioritize, and reduce variation; however, it did not determine "to what extent possible." Future research should examine thresholds of variation reduction to determine what level of variation acceptable, or what types of variation are simply inherent to the construction process and should not be targeted for reduction (i.e. how Lean is Lean enough?).

5.6 Scholarly Contributions

5.6.1 Journal Papers

There are four papers planned for publication in the *Journal of Construction Engineering and Management* based on this research. The papers are in different levels of submission and acceptance, but are summarized below in Table 5.2:

Table 5.2: Journal paper titles and publication status

Paper Title	**Status**
Causes of Variation in Construction Project Task Starting Times and Duration	Accepted for publication
Using Last Planner® and a Risk Assessment Matrix to Reduce Variation in Mechanical Related Construction Tasks	Revisions made based on review comments – waiting for 2nd review or acceptance
Using Pajek and Centrality Analysis to Identify a Social Network of Construction Trades	Submitted and awaiting initial reviewer comments
A Case Study into Task Variation and the Social Network of Construction Trades	Submitted and awaiting initial reviewer comments

5.6.2 Conference Papers / Presentations

The initial versions of three of the planned journal papers were also included with various construction engineering related conferences, which are listed below.

- ASCE Construction Institute's 2010 Construction Research Congress (May 2010) in Banff, Alberta, Canada. A paper titled, "Causes of Variation in Construction Task Starting Times and Duration," was presented and published in the conference proceedings.

- 2011 CSCE Annual General and Construction Specialty Conference (June 2011) in Ottawa, Ontario, Canada. A paper titled, "Planning to Reduce Variation in Mechanical Related Construction Tasks," has been accepted for inclusion in the conference.

- 19th Annual Conference for the IGLC (July 2011) in Lima, Peru. The abstract for a paper titled, "A Case Study into Task Variation and the Social Network of Construction Trades," has been accepted.

REFERENCES

Alarcón, L.F. et al. (2005). "Assessing the Impacts of Implementing Lean Construction." Proceedings of the 13th Annual Conference of the International Group for Lean Construction, July, Sydney, Australia, pp. 387-393.

Ballard, G. (1997). "Lookahead Planning: The Missing Link in Production Control." Proceedings of the 5th Annual Conference of the International Group for Lean Construction, July, Griffith University, Gold Coast, Australia.

Ballard, G. (2000) *The Last Planner System of Production Control.* PhD thesis, Dept. of Civil Engineering, University of Birmingham, Birmingham, U.K.

Ballard & Howell (1998), "Shielding Production: Essential Step in Production Control." *Journal of Construction Management & Engineering,* ASCE, New York, NY, 124(1) pp. 11-17.

Ballard, G., Koskela, L. J., Howell, G. A., and Tommelein, I. D. (2003) "Discussion of 'Improving Labor Flow Reliability for Better Productivity as Lean Construction Principle'" ASCE, J. Constr. Eng. Mgmt., May/June, Vol. 129, No. 3, pp. 251–261.

Barnes, J. A. (1954) "Class and Committees in a Norwegian Island Parish", Human Relations 7:39–58

Belton, V. and Stewart, T.J. (2002) *Multiple Criteria Decision Analysis*. Kluwer Academic Publishers, Boston, MA.

Borcherding, J., and Garner, D. (1981) "Work force motivation and productivity on large jobs." J. Constr. Div., Vol. 107, No. 3, pp. 443–453.

Chinowski, P., Diekmann, J., and Galotti, V. (2008) "Social Network Model of Construction." J Constr. Eng. and Mgmt., October, pp. 804-812.

Choo, H.J., Tommelein, I.D., Ballard, G., and Zabelle, T.R. (1999). "WorkPlan: Constraint-based Database for Work Package Scheduling." Journal of Construction Engineering and Management – ASCE, Volume 125, Issue 3, pp. 151-160.

Comrey, A.L. and Lee, H.B. (1992) A First Course in Factor Analysis. Lawrence Erlbaum Associates, Inc., Publishers. Hillsdale, NJ.

Chua, D.K.H., and Godinot, M. (2006) "Use of a WBS Matrix to Improve Interface Management in Projects." J Constr. Eng. and Mgmt., January, pp. 67-79.

Cureton, E.E. and D'Agostino, R.B. (1983) *Factor Analysis: An Applied Approach*, Lawrence Erlbaum Assoc., Hillsdale, N.J.

Dai, J., Goodrum, P. M., and Maloney, W. F. (2009) “Construction Craft Workers’ Perceptions of the Factors Affecting Their Productivity.” J Constr. Eng. and Mgmt., Vol. 135, No. 3, March 1, pp. 217-226.

Di Marco, M.K., Taylor, J.E., and Alin, P. (2010) “Emergence and Role of Cultural Boundary Spanners in Global Engineering Project Networks.” J of Mgmt. in Eng, July 2010, pp 123-132.

Doloi, H. (2007) “Twinning Motivation, Productivity and Management Strategy in Construction Projects.” *Engineering Management Journal* Vol. 19 No. 3 September, pp. 30-40.

Edwards, W. (1977) How to use multiattribute utility measurement for social decision making. *IEEE Trans. Systems, Man, Cybernetics* (SMC-7) 326–340.

Edwards, W., F. H. Barron. (1994) SMARTS and SMARTER: Improved simple methods for multiattribute utility measurement. *Organ. Behavior Human Decision Processes* 60(3) 306–325.

Erlang, A.K. (1909). "The Theory of Probabilities and Telephone Conversations", Nyt Tidsskrift for Matematik B, Vol 20.

Farid, F., and Koning, T.L. (1994). "Simulation verifies queuing program for selecting loader truck fleets." J. Constr. Eng. and Mgmt., ASCE, 120(2), pp. 386-404.

Field, A. (2005) *Discovering Statistics Using SPSS, 2nd* Ed., SAGE Publications.

Field Manual (FM) 100-14 (1998). *Risk Management.* Headquarters, Department of the Army, Washington, DC, 23 April.

Galbraith, J. R. (1977) Organization Design. Reading, MA, Addison-Wesley.

Gass, S. I. (1998) Tournaments, transitivity and pairwise comparison matrices. *J. Oper. Res. Soc.* 49(6) 616–624.

Gass, S. I. (2005) “Model World: The Great Debate—MAUT versus AHP” Interfaces Vol. 35, No. 4, July–August 2005, pp. 308–312.

Gomar, J.E., Hass, C.T., and Mortan, D.P. (2002) “Assignment and Allocation Optimization of Partially Multiskilled Workforce.” J. Constr. Eng. and Mgmt., Mar/Apr, pp. 103-109.

González, V., Alarcón. L.F., Maturana, S., Mundaca, F., and Bustamante, J. (2010) “Improving Planning Reliability and Project Performance Using the Reliable Commitment Model.” J. Constr. Eng. and Mgmt., October, pp. 1129-1139.

Hagen, L. and Kahng, A.B. (1992) “New Spectral Methods for Ratio Cut Partitioning and Clustering.” IEEE Transactions on Computer-Aided Design, Vol. 11, No. 9, pp. 1074-1085.

Harmon, H.H. (1976) Modern Factor Analysis, 3d Ed., University of Chicago Press, Chicago.

Hanna, A.S., Camlic, R., Peterson, P.A, and Lee, M-J (2004) “Cumulative Effect of Project Changes for Electrical and Mechanical Construction.” J. Constr. Eng. and Mgmt., Nov/Dec, pp. 762-771.

Hanna, A.S., Peterson, P., and Lee, M. (2002) “Benchmarking Productivity Indicators for Electrical/Mechanical Projects.” J. Constr. Eng. and Mgmt., Jul/Aug, Volume 128, Issue 4, pp. 331-337.

Herbsman, Z., and Ellis, R. (1990) “Research of factors influencing construction productivity.” Construction Management and Economics, V8, pp. 49-61.

Horman, M.J. and Thomas, H.R., (2005) “Role of Inventory Buffers in Construction Labor Performance.” J. Constr. Eng. and Mgmt., July, pp. 834-843.

Howell, G. A, and Ballard, G. (1994) “Implementing Lean Construction: Reducing Inflow Variation.” 2nd Annual Conference on Lean Construction, Catolica Universidad de Chile Santiago, Chile, September.

Howell, G.A., Ballard, G., and Hall, J. (2001) “Capacity Utilization and Wait Time: A Primer for Construction.” Proceedings of IGLC-9, Singapore, Korea, 6 – 8 August.

Howell, G. A., Ballard, G., Tommelein, I.D., and Koskela, I. (2004) “Discussion of ‘Reducing Variability to Improve Performance as a Lean Construction Principle.’” ASCE, J. Constr. Eng. Mgmt., Mar/Apr, pp. 299-304.

Hsiang, S.M. (personal email communication, May 15, 2010) notes about the analytical hierarchy process.

Ibbs, W., Nguyen, L.D., and Lee, S. (2007) “Quantified Impacts of Project Change.” J. of Professional Issues in Eng. Education and Practice, January, pp. 45-52.

Kaiser, H. F. (1974). “An index of factorial simplicity.” *Psychometrika*, 39(1), 31–36.

Keeney, R. L., H. Raiffa. (1976) *Decisions with Multiple Objectives*. John Wiley and Sons, New York.

Kim, J.O. and Mueller, C. W. (1978) Introduction to Factor Analysis. Sage University Paper Series on Quantitative Applications in the Social Sciences, 07-013. Newbury Park, CA: Sage.

Kimpland, Scott L. (2009) "2009 Contractor Productivity Survey Results." FMI Corporation, Raleigh, NC.

Koskela, L.J. (2000) "An exploration towards a production theory and its application to construction." PhD thesis, Teknillinen Korkeakoulu (Helsinki), Finland.

Lawley, D.N. and Maxwell, A.E. (1971) Factor Analysis as a Statistical Method, 2d Ed., Butterworths, London.

Liberda, M., Ruwanpura, J., and Jergeas, G. (2003) "Construction productivity improvement: A study of human, management and external issues." Proc., Construction Research Congress, ASCE, Reston, Va.

Liu, M. and Ballard, G. (2009). "Factors Affecting Work Flow Reliability – A Case Study." Proceedings of the 17th Annual Conference of the International Group for Lean Construction (IGLC 17), 15-17 July, Taipei, Taiwan, pp.657-666.

Lu, W., Shen, L., and Yam, M.C.H. (2008) "Critical Success Factors for Competitiveness of Contractors: China Study." *Journal of Construction Engineering and Management*, Vol. 134, No. 12, December 1, pp. 972-982.

Meredith, J. (1998). "Building operations management theory through case and field research." *J. Operations Management*, 16(4), 441–454.

Moreno, J. L. (1960). *The sociometry reader*, The Free Press, Glencoe.

Ohno, T. (1988). *Toyota Production System: Beyond large-scale production*, Productivity Press Inc. Cambridge, Mass

Paul, K. (1994). *An easy guide to factor analysis*, Routledge, New York.

Pett, M.A., Lackey, N.R., and Sullivan, J.J. (2003) *Making Sense of Factor Analysis*, Sage Publications, California.

Portas, J. and AbouRizk, S. (1997) "Neural Network Model for Estimating Construction Productivity." J Constr. Eng. and Mgmt., Vol. 123 (4), pp. 399-410.

Radosavljevic, M. and Horner, R.M.W. (2002) “The evidence of complex variability in construction labour productivity.” Construction Management and Economics, Vol 20, pp. 3-12.

Rilett, L. R. (1998) “Identifying Component Variability of End Product Specification Tests.” J. Constr. Eng. Mgmt., Mar/Apr, pp. 133-138.

Rojas, M., and Aramvareekul, P. (2003) “Labor productivity drivers and opportunities in the construction industry.” J. Manage. Eng., V 19(2), pp. 78–82.

Roy, B. 1996. *Multicriteria Methodology for Decision Aiding*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Saaty, R.W. (1987) *The analytic hierarchy process—what it is and how it is used.* Published by Elsevier Science, 4922 Ellsworth Avenue, Pittsburgh, PA 15213, U.S.A.
Saaty, T. L. (1980). *The analytic hierarchy process*, McGraw-Hill, New York.

Saaty, T. L. (1987) Rank generation, preservation, and reversal in the analytic hierarchy decision process. *Decision Sci.* 18(2) 157–177.

Saaty, T.L. and Vargas, L.G. (1994) *Models, methods, concepts, and applications of the Analytical Hierarch Process,* Kluwer Academic Publishers, Norwell, MA 02061.

Saaty, T.L. (2008) “Decision making with the analytic hierarchy process”, *Int. J. Services Sciences*, Vol. 1, No. 1, pp.83–98.

Shapira, A. and Simcha, M. (2009) “AHP-Based Weighting of Factors Affecting Safety on Construction Sites with Tower Cranes.” J. Constr. Engrg. and Mgmt. Volume 135, Issue 4, pp. 307-318

Somnez, R., and Rowings, J. E., (1998) “Construction Labor Productivity Modeling with Neural Networks.” J Constr. Eng. and Mgmt., Vol. 124, No. 6, Nov/Dec, pp. 498-504.

Spearman, C. (1927) The abilities of man. Oxford, England: Macmillan. (1927).

Tellis, W. (1997). Introduction to case study [68 paragraphs]. *The Qualitative Report* [On-line serial], *3*(2). Available: http://www.nova.edu/ssss/QR/QR3-2/tellis1.html

Thomas, H. R. and Yiakoumis, I. (1987) “Factor Model of Construction Productivity.” J. Constr. Eng. Mgmt., Vol. 113, No. 4, December, pp. 623-639.

Thomas, H. R. and Sakarcan, A. S. (1994) “Forecasting Labor Productivity using Factor Model.” J. Constr. Eng. Mgmt., Vol. 120, No. 1, March, pp. 228-239.

Thomas, H. R., Horman, M. J., Lemes de Souza, U. E., and Zavrski, I. (2002) "Reducing Variability to Improve Performance as a Lean Construction Principle." ASCE, J. Constr. Eng. Mgmt., Mar/Apr, Vol 128, No. 2, pp. 144-154.

Tommelein, I. D., Riley, D. R., and Howell, G. A. (1999) "Parade game: impact of work flow variability on trade performance." J. Constr. Eng. Mgmt., Sep/Oct, pp. 304-310.

Trost, Steven M. and Oberlender, Garold D. (2003) "Predicting Accuracy of Early Cost Estimates Using Factor Analysis and Multivariate Regression." J Const. Eng. Mgmt., Mar/Apr, pp. 198-204.

Uncertainty. (2011). Merriam-Webster Online Dictionary. Retrieved 3 Feb, 2011 from http://www.merriam-webster.com/dictionary/uncertainty

Vargas, L.G. and Hsiang (2010) "COMPARISON OF THREE MULTICRITERIA DECISION MAKING THEORIES: The Analytic Hierarchy Process, Multiattribute Utility Theory and OutRanking Methods" University of Pittsburg. (Unpublished paper written by Vargas and obtained from Hsiang, May 2010)

Wambeke, B.W., Hsiang, S.M., and Liu, M. (2011) "Causes of Variation in Construction Project Task Starting Times and Duration." *J Const. Eng. Mgmt.*, TBD

Winch, G.M. (2002) Managing Construction Projects, Blackwell Publishing, Oxford, UK.

Yin, R. (1994). *Case study research: Design and methods* (2nd ed.). Thousand Oaks, CA: Sage Publishing.

Zhang, G. and Zou, P.X.W. (2007) "Fuzzy Analytical Hierarchy Process Risk Assessment Approach for Joint Venture Construction Projects in China" J. Constr. Engrg. and Mgmt. Volume 133, Issue 10, pp. 771-779.

Zhang, X. (2006) "Factor Analysis of Public Clients' Best-Value Objective in Public–Privately Partnered Infrastructure Projects." *Journal of Construction Engineering and Management*, Vol. 132, No. 9, pp, 956-965.

APPENDICES

APPENDIX A. VARIATION SURVEY

1. Survey Introduction

Thank you for taking the time to complete this survey. It should take you about 15-20 minutes to complete.

The overall intent of this survey is to determine what causes the variation in start times and duration of construction tasks. You can think of "variation" as the difference between what was planned and what actually happened. For example, your 4 person crew planned to start hanging sheetrock at 8:00 am, but were delayed for 60 minutes because you were waiting for a forklift to move the sheetrock. In this case the variation in the task start time would be 1 hour and it would affect 4 people.

The sub-objectives (more specific than the overall intent) of the survey are:

1) Determine and examine any differences of opinion/perception between how project managers, supervisors, and skilled craftspersons/laborers view the causes/impacts of variation in start times and duration of construction tasks.

2) Identify the most prevalent factors of variation in terms of:
- What type/magnitude of variation is always present and is relatively constant.
- What type/magnitude of variation happens on occasion or fluctuates in magnitude.

Instructions are included throughout the survey to clarify what is being asked of you. Simply provide what you feel is the best answer based on your personal experience and/or opinion. Your responses will remain anonymous as your name is not included in the survey.

Please return the surveys to me by 30 AUG 09. Consolidate them by company and mail them to the address below. If you would like a copy of the survey results, simply contact me via email.

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2. General information

1. Please indicate what state you are currently working in.

State:

* **2. What best describes the type of company you work for?**

- Subcontractor
- General Contractor

Other (please specify)

* **3. What size would you estimate your company to be (including both permanent and the average number of temporary employees)?**

- Small (25 employees or less)
- Medium (25 - 150 employees)
- Large (more than 150 employees)

* **4. What would you estimate the overall annual revenue of your company to be?**

- < $100k
- $100k - $500k
- $500k - $1M
- $1M - $5M
- $5M - $15M
- $15M - $25M
- $25M - $50M
- $50M - $100M
- $100M - $200M
- > $200M
- I don't know

* **5. What would you estimate to be the average project size you typically work on?**

- < $100k
- $100k - $500k
- $500k - $1M
- $1M - $5M
- $5M - $15M
- $15M - $25M
- $25M - $50M
- $50M - $100M
- $100M - $200M
- > $200M
- I don't know

* **6. What would you estimate the distribution of your work to be? The total should add up to 100%.**

	Percent
Public sector	
Private sector	
I don't know	

* 7. How would you describe your company's backlog (i.e. how much pending work does your company have lined up)?

- Large backlog - work lined up for the next 1-2 years
- Moderate backlog - work lined up for next 6 months to 1 year
- Little to no backlog - less than 6 months of future work lined up
- I don't know about the company's backlog

Other (please specify)

* 8. Do you work under a union?

- Yes
- No
- Unsure

* 9. Which best describes your job position / duty?

- Laborer / Skilled Craftsperson
- Supervisor / Foreman
- Superintendent / Project Manager

* 10. Which trade or area of construction best describes your work?

- Piping / Plumbing
- Mechanical / HVAC
- Electrical
- Concrete
- Steel
- Roofing / Drywall / Masonry
- Earthwork / Highway / Road building

Other (please specify)

* 11. What is your experience level?

	In the construction industry	In your current position
Years of experience (round to nearest number of years)		

* 12. How many hour of overtime do you typically work in a week? Assume 40 hours is a standard week and anything over that is overtime.

3. Overall Category Comparison

The purpose of this page is to compare eight different areas by rank ordering them based upon how much they contribute to the variation of task start times and task duration times. Recall, variation is the difference between what was planned and what actually happened. Consider what you plan to do (in terms of starting times and anticipated duration times) as the base line. A couple examples are shown below to further explain variation of starting times and duration.

START TIME VARIATION example: You plan to start a task at 8:00 every day during the week, but on average you end up starting late one hour each week (due to something). In this case, the average weekly variation in task start time would be 1 hour.

TASK DURATION VARIATION example: The anticipated duration is how long you expect a task to take and is often based upon the schedule. Even if you start late, the duration could still be the same (i.e. you expect the task to take the same amount of time to complete, regardless of when you actually start it). If for example, you take an extra 3 hours per week to complete your scheduled work (not because you started late, but because the work just took longer than expected), the average weekly variation in duration would be 3 hours.

The eight areas, along with a general description of each, are:

1) Prerequisite Work: Pertains to items that must be completed before you can start a task
2) Detailed Design / Working Method: Having an accurate and available design/drawing and a feasible working method
3) Labor Force: Having an available labor force trained to perform the required task(s)
4) Tools/Equipment: Required tools/equipment are available in sufficient quantities and conditions
5) Material and Components: Having the correct and necessary materials available when and where you need them.
6) Work / Jobsite Conditions: Having adequate physical space available to perform your job
7) Management/Supervision/Information Flow: Is there a system in place to develop the work plan and schedule, provide guidance/instruction, and to answer questions when they arise
8) Weather or External Conditions: Items that occur which are outside the control of those in your company.

* **1. Please rank order the eight overall categories based upon how much you feel they contribute to the variation of both the task start times and task duration times (i.e. one for each column below). For example, if you believe the labor force causes the greatest amount of variation in task start times, then you would rank labor force as #1 under the task start time column. If you feel tools and equipment causes the greatest amount of variation for the duration of a task, then it would be ranked #1 under the task duration column.**

Note - there should be a #1 - #8 in each column when you are finished with the ranking.

	Variation of Task Start Time	Variation of Task Duration
Prerequisite work		
Detailed design and working method		
Labor force		
Tools and equipment		
Materials and components		
Work / Jobsite conditions		
Supervision / Management / Information Flow		
Weather or external conditions		

* **2. In your opinion, which do you feel is better?**

Wait for all resources: Waiting to start working until all the required resources (material, people, tools, equipment, etc.) are available, even though this may delay getting started. You feel a possible delayed start is justified by the efficiency gained when you have all the appropriate resources.

"Make do" with what you have: Be flexible and start working as long as there are enough resources to get started. It is better to do some work rather than none, and accept the fact the task duration may be extended if you don't end up receiving all of the anticipated resources.

- ◯ Wait to start until you have all of the planned resources
- ◯ "Make do" - begin work when you have enough resources to start

* **3. How often do you actually follow or experience the option you feel is best (from the previous question)?**

- ◯ Almost always (>95% of the time)
- ◯ Usually (about 75% of the time)
- ◯ About half the time (50%)
- ◯ Seldom (about 25% of the time)
- ◯ Almost never (<5% of the time)

The majority of the survey from this point on deals with the variation of task starting times and task duration times. Specifically, it's asking how many actual hours (not labor-hours), during an average week, you are delayed or you spend waiting on the various items listed along the left hand side of several questions. These questions are broken down into the eight categories previously mentioned (the ones you rank ordered), but the procedure is the same for each question – simply estimate the variation (the difference between what was planned and what happened) in terms of the task start time and task duration. Additionally, you will indicate how many people this impacts (most likely: just you, the number in your crew, or the number you supervise). There are separate columns for the start time variation, the duration variation, and the number of people impacted.

This example illustrates how to determine the variation of start times and duration. Imagine your average week consisted of completing three tasks.

Task 1 is scheduled to start on Monday at 8:00 am and take 16 hours to complete (finish at 5:00pm on Tuesday). You actually don't start until 10:00am and then finish at 7:00pm on Tuesday (duration was still 16 hours). In this case the start time variation would be 2 hour and the duration variation would be zero.

Task 2 is scheduled to start at 8:00am on Wednesday and take 8 hours to complete (finish at 5:00pm on Wednesday). You actually start at 8:00am, but it takes you until 6:00pm to complete it. In this case, the start time variation would be zero and the duration variation would be 1 hour.

Task 3 is scheduled to start at 8:00am on Thursday and take 16 hour to complete (finish at 5:00pm on Friday). You actually start at 9:00am and don't finish until 7:00pm on Friday. In this case, the start time variation would be 1 hour and the duration variation would be one hour since the task actually took 17 hours to complete.

So, if this example represented an average week, the total weekly start time variation would be 3 hours and the duration variation would be 2 hours.

Now, consider your typical week and think about what causes variation in your start times and duration times. As you work through the remainder of the survey, the "reasons" for the variation are listed along the left hand side of the questions. When they apply to you (i.e. that's the reason you experience variation), simply fill out that row. If you don't know about one of the items or if it doesn't apply to you, you can leave it blank or place a zero in the space provided.

4. Prerequisite work

* **1. These items pertain to PREREQUISITE WORK. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect? Break down the variation between the task start time and the task duration. Recall, variation is the difference between what was planned to happen and what actually happened. Base your responses on how you, your crew, or those you supervise are impacted.**

For example, a crew of 5 people are delayed an average of 3 hours per week to start their tasks because they are waiting on a required permit. In this case, there would be a variation in the task start time of 3 hours and it would impact 5 people. The task duration would not be impacted.

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
Obtaining required permits for the work to begin				
Completion of previous work (i.e. work before you isn't done yet)				
Rework being required due to the quality of previous work				
Poor quality of previous work (though not to a level that requires rework) causes a delay				
Inspections for previously completed work				

2. Please indicate if there is another significant cause (with respect to prerequisite work) that results in you having to wait or be delayed during an average week.

Cause of variation

Hours per week affected (start and duration)

Number of people impacted

5. Detailed design and working method

* **1. This section pertains to the DESIGN or WORKING METHOD. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect?**

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
Design constructability				
Quality of documents (errors in design and/or drawings)				
Turnaround time from engineers when there is a question with a drawing				
Strict specification requirements				
Quality control requirements				
Work complexity				
Work sequence or method is not well planned				
Low degree of repetition (inability to develop efficient system due to task constantly changing)				
Inadequate instruction on detailed working method				

2. Please indicate if there is another significant cause (with respect to the design or working method) that results in you having to wait or be delayed during an average week.

Cause of variation	
Hours per week affected (start and duration)	
Number of people impacted	

6. Labor Force

* **1. This section pertains to the LABOR FORCE. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect?**

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
Socializing (talking with fellow workers)				
Absenteeism				
People arriving late and/or leaving early due to illness, injury, family or personal situation, etc.				
Low morale and/or lack of motivation				
Getting moved to another job/task before the one you were working on was completed and/or before scheduled to move				
The crew size being inadequate (i.e. smaller than normal for your company or smaller than what is typical in the industry) for a particular type of work				
Inefficiencies associated with personnel turnover (i.e. new employees)				
Experience on similar tasks (i.e. there is a learning curve associated with non-repetitive tasks)				
Worker/crew lack of skills/experience to perform the task(s) being asked of them				
Language barrier among workers and/or worker-supervisor				

* 2. What best describes the situation or the reason you (or your workers) get reassigned to perform a different task before the one you were working on was completed?

- [ ] N/A - we don't get reassigned
- [ ] It's due to schedule changes or project acceleration
- [ ] Having to juggle several jobs/tasks and not being able to completely finish one at a time (shifting priorities or overcommitment)
- [ ] Lack of coordination and/or planning to synchronize different trades
- [ ] Another trade is behind/ahead of schedule and causes the reassignment

Other (please specify)

* 3. Does your employer offer the ability to attend specialized training (trade or craft specific, communications, planning, etc.) outside what you learn on the job?

- [ ] Yes
- [ ] No
- [ ] I don't know

4. Have you received any specialized training (outside what you get on the job) to enhance your ability to do your job?

- ○ Yes
- ○ No (skip questions 5-7)

5. What type of specialize training did you receive?

6. What is the estimated number of hours of training you received?

7. Who funded the training?

- ○ Employer
- ○ Self funded
- ○ Grant or scholarship

Other (please specify)

8. Please indicate if there is another significant cause (with respect to the labor force) that results in you having to wait or be delayed during an average week.

Cause of variation

Hours per week affected (start and duration)

Number of people impacted

7. Tools / Equipment

* 1. This section pertains to TOOLS & EQUIPMENT. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect?

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
Personnel lift				
Power tools				
Crane or forklift				
Hand tools				
Other heavey equipment (backhoe, loader, dump truck, etc.)				
Personal protective equipment				

* 2. What best describes the situation or the reason you (or your workers) wait for a personnel lift?

- [ ] N/A - we don't wait on a personnel lift
- [ ] Lift is available, but a qualified operator is not available
- [ ] Lift and operator are available, but lift is idle because you are not next in priority
- [ ] Lift if being used by someone else
- [ ] Maintenance

Other (please specify)

* 3. What best describes the situation or the reason you (or your workers) wait to use power tools?

- [ ] N/A - we don't wait on power tools
- [ ] Not all crew members trained/qualified to use
- [ ] Power tools are being used by someone else
- [ ] They are misplaced or lost
- [ ] Maintenance status

Other (please specify)

*** 4. What best describes the situation or the reason you (or your workers) wait for a crane or forklift?**

- [ ] N/A - we don't wait on a crane or forklift
- [ ] Crane/FL is available, but a qualified operator is not available
- [ ] Crane/FL and operator are available, but it is idle because you are not next in priority
- [ ] Crane/FL if being used by someone else
- [ ] Crane/FL maintenance status

Other (please specify)

*** 5. What best describes the situation or the reason you (or your workers) wait to use hand tools?**

- [ ] N/A - we don't wait on hand tools
- [ ] Hand tools are being used by someone else
- [ ] They are misplaced or lost
- [ ] They are broken

Other (please specify)

*** 6. What best describes the situation or the reason you (or your workers) wait due to PPE?**

- [ ] N/A - all workers have necessary PPE
- [ ] Not enough PPE for all workers - being used by someone else
- [ ] PPE is misplaced or lost
- [ ] PPE is unserviceable

Other (please specify)

7. Please indicate if there is another significant cause (with respect to tools/equipment) that results in you having to wait or be delayed during an average week.

Cause of variation

Hours per week affected (start and duration)

Number of people impacted

8. Material and Components

* **1. This section pertains to MATERIALS & COMPONENTS. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect?**

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
Material to be moved to where you need it				
Material to arrive from distributor or supplier				
Trying to get consumables				
Due to an error in material size				
Due to an error in material type				

* **2. What best describes the situation or the reason you (or your workers) wait for material to be moved?**

- ☐ N/A - we don't wait on material to be moved
- ☐ Lack of equipment or qualified operators to move material
- ☐ You are not the priority
- ☐ Previous coordination didn't take place (i.e. no one knew you needed material moved)
- ☐ Maintenance
- ☐ Physical distance between material storage and work place causes delays

Other (please specify)

* **3. What best describes the situation or the reason you (or your workers) wait for materials to arrive?**

- ☐ N/A - we don't wait on materials to arrive
- ☐ Supplier is behind schedule
- ☐ We are ahead of schedule and supplier needs to react
- ☐ Schedule change causes us to require material earlier
- ☐ Lack of coordination to synchronize our schedule with material delivery

Other (please specify)

* **4. What best describes the situation or the reason you (or your workers) wait for consumables?**

- [ ] N/A - we don't wait for consumables
- [ ] Lack sufficient quantities of consumables at jobsite
- [ ] Lack of planning - didn't anticipate they would be required

Other (please specify)

* **5. What best describes the situation or the reason you (or your workers) wait because of an error with material size?**

- [ ] N/A - we don't wait due to material size errors
- [ ] Error by fabricator or person that performed previous work
- [ ] Change in drawing/design didn't get to fabricator in time
- [ ] Error with drawing/design

Other (please specify)

* **6. What best describes the situation or the reason you (or your workers) wait because of an error with material type?**

- [ ] N/A - we don't wait due to material type errors
- [ ] Error by fabricator or person that performed previous work
- [ ] Change in drawing/design didn't get to fabricator in time
- [ ] Error with drawing/design

Other (please specify)

7. Please indicate if there is another significant cause (with respect to material) that results in you having to wait or be delayed during an average week.

Cause of variation

Hours per week affected (start and duration)

Number of people impacted

9. Work / Job Site

* **1. This section pertains to the WORK / JOB SITE. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect?**

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
Overcrowded work area / Jobsite congestion				
Difficult access to work area				
Site layout - distance between material storage and where material is required for work				

* **2. What best describes the situation or the reason you (or your workers) are delayed due to jobsite congestion?**

- ☐ N/A - we don't wait due to jobsite congestion
- ☐ It's just part of construction and is unavoidable
- ☐ Another trade is behind/ahead of schedule
- ☐ It's due to schedule changes or project acceleration
- ☐ Lack of coordination and/or planning to synchronize different trades

Other (please specify)

3. Please indicate if there is another significant cause (with respect to the jobsite) that results in you having to wait or be delayed during an average week.

Cause of variation

Hours per week affected (start and duration)

Number of people impacted

10. Management / Supervision / Information Flow

* **1. This section pertains to MANAGEMENT / SUPERVISION / INFORMATION FLOW. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect?**

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
To get answers to questions you have about the design or drawing				
For guidance or instruction from your supervisor				
Lack of field manager (foreman) skill/knowledge				
Coordination between different trades				
Over commitment due to a tight work schedule				
Foreman availability				
Change in the scope of work				
Foreman communication skills				
Communication between Owner/Engineer and project manager				
Communication between project manager and foremn				
Communication between foreman and workers				

* **2. Select the organizational structure that best illustrates how information or decisions made by the owner get passed to you.**
AE = Architect / Engineer, GC = General Contractor, Sub = Subcontractor

- ◯ Owner - you (1 layer)
- ◯ Owner - AE or GC - you (2 layers)
- ◯ Owner - AE - GC - you (3 layers)
- ◯ Owner - AE - GC - Sub - you (4 layers)
- ◯ Owner - AE - GC - Sub - Sub - you (5 layers)

Other (please specify)

* **3. How often do you receive guidance or instruction from your supervisor? Consider guidance or instruction on items such as: daily/weekly goals, overall project status, the work method, or the schedule.**

- ◯ Never
- ◯ About monthly
- ◯ 2-3 times/month
- ◯ Weekly
- ◯ 2-3 times/week
- ◯ Daily

Other (please specify)

* **4. Does your supervisor (or you if you are a supervisor) typically listen to / implement recommendations from the field on potential improvements to the work method or process being used?**

- ◯ No
- ◯ Listens, but doesn't make any changes
- ◯ Listens and makes changes

5. Please indicate if there is another significant cause (with respect to supervision, management, or information flow) that results in you having to wait or be delayed during an average week.

Cause of variation

Hours per week affected (start and duration)

Number of people impacted

11. Weather / External Conditions

* **1. This last section pertains to EXTERNAL FACTORS. How many weekly hours (actual hours) of variation (time spent waiting or delayed) do you experience due to them and how many how many people does this generally affect?**

	Start time variation - actual hours delayed	Start time - number of people impacted	Task duration variation - actual hours delayed	Task duration - number of people impacted
Weather impacts (excessive heat, cold, wind, rain, etc.)				

2. Please indicate if there is another significant cause of variation due to external conditions (things you and/or your manager/supervisor can't control) that result in you having to wait or be delayed during an average week.

Cause of variation

Hours per week affected (start and duration)

Number of people impacted

3. If there is anything else that you would like to add pertaining to variability of task starting times and durations, please provide it here:

*********************************** THIS CONCLUDES THE SURVEY ***********************************

Thank you for your time and input. If you would like a copy of the results, please contact me at via email. Once again, please return the completed survey to me at the address below by 30 August 2009.

Sincerely,

Brad Wambeke
PhD Graduate Student
Mann Hall - Room 218
Department of Civil, Construction, and Environmental Engineering
North Carolina State University
Raleigh, NC 27695-7908
bwwambek@ncsu.edu

APPENDIX B. EXAMPLE CASE STUDY PROPOSAL

NC STATE UNIVERSITY

30 October 2009

[redacted]

RE: PROPOSAL FOR RESEARCH OF PLANNING/COMPLETION OF FIELD TASKS

Dear [redacted]

It was great to meet you and listen to your presentation in Boulder at the LCI conference. Based upon our brief discussion there with [redacted] I am aware of your potential interest in supporting my research at North Carolina State University. Attached to this letter is a proposal for the objectives, scope and work plan associated with this effort.

I am a lieutenant colonel in the US Army and am working on a PhD prior to an assignment as one of the senior faculty members in the Civil and Mechanical Engineering Department at West Point. I am planning to implement and teach a project management course once there. I am researching variation in task starting times and duration as both can directly impact project performance.

My experience in the military is that when a unit conducts after action reviews and then implements the results, their performance increases. I think that can be said for most organizations; the ones that are willing to look critically at themselves and find opportunities to improve are the ones that are the most successful. Based upon your presentation at the LCI conference, your company has done an exceptional job at finding ways to improve. I hope you will look at this case study as an opportunity to potentially identify another area to improve or, at a minimum, confirm that you are already handling variation very efficiently. I am interested in studying two to four of your projects during the next year.

I would like to review this proposal over the phone with you an [redacted] in the next week. I will contact you early next week at [redacted] to set up a time when the three of us can discuss the proposal.

Best Regards,

Brad Wambeke

Brad Wambeke
Ph.D. Candidate
North Carolina State University
Email: bwwambek@ncsu.edu
Phone: (910) 988-9488
c: Min Liu (NC State) [redacted]

BACKGROUND AND OBJECTIVE:

Schedule-oriented variation in construction tasks is a routine occurrence on construction projects and impacts the overall performance of a contractor's team, yet the root causes of this particular variation are elusive. Variation can impact key performance indicators (KPIs) such as decreasing field productivity, increasing direct and indirect costs, and reduce customer satisfaction by delaying completion/turnover schedules. This variation is so costly to contractors because once a task delay event occurs (i.e., task not starting on time or task taking longer than anticipated), there is nothing that can be done to recover the opportunity cost of that lost time.

There are two fundamental schools-of-thought which differ in that one is based on a traditional approach of accepting the variation but reducing the impacts of the variation to the project and the other is focused on preventing and minimizing variation altogether. The traditional approach is to maintain adequate sized buffers and use flexibility to deal with the variation. An example of this is to complete a significant amount of work and make it ready for quality inspection, and then re-direct the crew to non-planned activities for the day. The progressive strategy of prevention is to eliminate or minimize the variation in advance of the work execution through comprehensive collaborative planning and/or preparation and applying Lean principles.

This research involves investigating the factors that contribute to the variation of the starting times and duration of value-added tasks associated with concrete restoration projects. Two companies will be involved with this study:

- - a large, top-tier specialty contracting company based that performs concrete (horizontal) restoration, masonry (vertical) restoration and roofing services. ses a traditional/flexible approach to crew and task scheduling across their 40 nationwide branches.
- a smaller specialty contractor based in that performs mostly masonry (vertical) restoration services. generally uses the collaborative planning approach for addressing the issue of variation and uses Lean processes throughout the firm from the administrative office to the field. In many ways,

The hypothesis of this research is that a collaborative approach to planning and executing value-added tasks and non-value-added but required tasks will result in a lower variation of task starting times and task durations. The objectives of this research are as follows:

1) Identify the root causes of the variation for value-added tasks in terms of:
   - Starting time variation: the difference between the planned and actual starting time
   - Duration variation: the difference between the planned and actual task duration
2) Identify the impact of variation on key performance indicators (KPIs).
3) Suggest strategies to reduce variation (i.e. strategies to control the root causes of variation and/or strategies to identify the optimal capacity buffer level to shield variation).

DELIVERABLES:

At the end of this study, a report containing the findings as well as a description of the investigation will be submitted and presented individually to The data and report will also be shared with of their monthly staff meetings. The findings will include the following:

1) The identification of the value-added tasks with the highest variation for each project.
2) A list of the highest impact root causes of variation in terms of starting time and duration.
3) A suggested strategy to reduce the variation in the value-added tasks and/or KPIs.

The findings from this report will also be incorporated into a Ph.D. thesis and are intended to contribute to the existing body of knowledge in the industry of Lean construction. No individual identities or opinions will be shared and the confidentiality of all parties will be strictly maintained.

SCOPE OF STUDY:

The variation of several crews, working independently or in sequence, from each company will be tracked while executing similar projects. The scope of this study is to evaluate two to four projects from each company.

In addition to comparing the results of each company with the other, the results of this study will compliment a survey pertaining to variation that was previously conducted by the researcher. The survey was based on perceptions of workers, supervisors, and project managers, rather than the empirical data that will be generated during this study.

WORK STEPS AND SCHEDULE:

Although this proposal does not contain specific dates, the anticipated timeframe for the planning of this study is between now and mid December 2009, with the execution phase of the study beginning around January 2010. The planning steps are detailed below:

After both have individually had an opportunity to read, understand and approve this proposal, both companies will submit a set of requested preliminary materials.

A joint teleconference between the researcher and both firms will kick off the study. During the teleconference, the scope of the study will be reviewed, projects to be included in the study will be selected, the specific tasks to be measured will be identified and the terms and procedures to be followed by the researcher and the company during the execution of the study will be refined. It is preferred to include discrete value-added and possibly non-value-added, but required, tasks in the study. The researcher will rely heavily on company input to determine the appropriate level of tasks to measure. There also needs to be a common definition of the starting time. If company X plans to start the demolition of a wall at 10:00am, does the carrying a bucket of tools to the wall at 10:00am constitute an on-time start or does the first time a tool is put to the wall constitute the starting time? Either may be fine; the important part is there needs to be a consistent definition. In terms of task completion, it is proposed that a task is considered to be complete when it meets the required specification(s). Once the task has been completed, the duration is simple to calculate. It is anticipated that this preliminary planning effort will require 1-2 follow-up discussions.

To initiate the execution phase, the researcher will schedule a 2-3 day visit with each company in order to:

- Conduct a face to face meeting with the company leadership.
- Inform the workers and supervisor(s) about the study that is going to be carried out and the data collection methods that will be used. It is important for all involved to understand the purpose of the study is not to "look over the workers' shoulders" to find out if they are doing something wrong. The purpose is to get an unbiased look into the variation of the tasks, without the crews changing their behavior due to the study. It will be important to express this to the workers so they do not modify their behavior because they are being measured. Doing so would invalidate the results; thus resulting in little to no benefit for the researcher or either of the companies involved with the study.
- Provide the crew supervisor / foreman with the tools required to gather and report the data required for the study. Due to the geographical location of the researcher and the projects, it is likely the crew supervisor / foreman will collect most of the data. The anticipated data for each of the value-added tasks associated with the jointly agreed upon project(s) are tentatively:
    - Date
    - Task (anticipated to be based on a one week out schedule)
    - How the work plan is made (scheduling system, etc.)
    - List of prerequisites and readiness when a task is started (i.e. materials, tools, equipment, labor force, etc.)
    - Crew size
    - Scheduled starting time Actual starting time Reason if different
    - Scheduled duration Actual duration Reason if different
    - Number of labor hours spent on task
    - Any requests for information (RFIs) generated/submitted
    - Planned / actual productivity (defined in terms of: output/labor hours)
- The list of data to be collected will be discussed prior to the first visit and will be finalized during the first visit. The items above are representative of the type of information that will be gathered.

The researcher may conduct intermittent 1-2 day visits depending on the duration of the projects to observe the crews. Any visits will be coordinated with the company leadership.

A final visit by the researcher will be used to present the findings/deliverables and discuss the results of the survey with the company management. The overall goal is to complete the research and present the findings no later than February 2010.

STAFFING:

The person in charge of performing the study is Brad Wambeke. He is a lieutenant colonel in the US Army and is a second-year Ph.D. Candidate in the Construction Engineering and Management Program (Department of Civil, Construction, and Environmental Engineering) at

NC STATE UNIVERSITY

North Carolina State University. He holds a Master's Degree in Civil Engineering and has served in the US Army for over 16 years, to include teaching for two years as an assistant professor in the Civil and Mechanical Engineering Department at the United States Military Academy (West Point). His Ph.D. advisors are Professors Min Liu and Simon M. Hsiang, both faculty members of North Carolina State University.

BUDGET:
This study will be performed at no cost to Western Construction / Joseph Gnazzo Company, including travel costs.

MEDICAL:
The researcher is insured by the US Army; therefore, there is no requirement for any medical associated coverage.

LEGAL:
The results of this study will be used for scientific investigation and peer-reviewed publication, as part of the researcher's Ph.D. work at NCSU. No individual identities or opinions will be shared and the confidentiality of all parties will be sustained. All data collected, analysis results, and findings of the study will be shared with for their review and release approval prior to the researcher publishing the findings.

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PRELIMINARY MATERIALS LIST:

1. Organization chart for the company.

2. List of projects / schedule to be executed between January – December 2010.

3. Examples of Key Performance Indicators (KPIs) for projects and for the company.

4. List of value-added tasks typically associated with company projects.

5. Project reports from the past two years if available. Preferred data includes, but not limited to:

- Project description, scope, and cost
- Weekly project schedule
- How the work plan was made (scheduling system, etc.)
- List of prerequisites and readiness when a task was started (i.e. materials, tools, equipment, labor force, etc.)
- Daily crew size (planned / actual)
- Scheduled starting time   Actual starting time   Reason if different
- Scheduled task duration   Actual task duration   Reason if different
- Number of labor hours spent on each task
- Any requests for information (RFIs) generated/submitted
- Planned / actual productivity (defined in terms of: output/labor hours)