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Predicting the Impact of Resource Delays on a Construction Project's Critical Path using Monte Carlo Simulation

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Predicting the Impact of Resource Delays on a Construction Project's Critical Path using Monte Carlo Simulation

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Industrial Engineering

by

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University of Arkansas
Bachelor of Science in Mechanical Engineering, 2016

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This thesis is approved for recommendation to the Graduate Council.

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Abstract

The construction industry is a complex and evolving industry, making the project manager's job of planning, organizing, and making decisions a difficult one. One of the most difficult decisions throughout a project is determining what resources are needed to complete a task by the deadline. Uncertainties cause risks within the schedule often creating delays for which the project manager must develop a mitigation plan once risks are identified. After conducting a review of the literature, no research was found examining the use of an analytical model to estimate the delays caused within the resource allocation process. If an analytical model could be developed to identify potential risks within the three largest resource categories of equipment, materials, and labor, the project manager could combine this information with his experience to help ensure the project is successfully completed. This in-depth case study focuses on creating a model using Microsoft Project, Microsoft Excel, and Palisade @Risk software to perform Monte Carlo simulation to predict potential delays prior to the start of the construction project. Interviews were conducted with a group of subject matter experts (SMEs), with varying levels of experience, to help gather insight into how the model should be developed to benefit the entire construction industry. Once the analysis was conducted, the model was validated by comparing the critical path of the schedule to an actual completed project where a historic brewery was converted into office space. An interview was conducted with the project manager who oversaw the project to determine if the results seemed reasonable and to see if the model results would have been useful at the start of the project. Because this research only performed a case study, no general conclusions about the entire industry can be made until it is tested on additional projects. In the future, the research can be expanded by incorporating the cost portion of the schedule, creating the model using other Monte Carlo software such as Probability Management's SIPmath

or Oracle's Crystal Ball, and applying the analytical model to other industries such as software development, manufacturing, or defense by changing the names of the resource categories.

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1. Introduction

1.1. Background Information

The construction industry is a complex and ever-changing industry, often including sets of tasks that needed to be completed within a specific timeline to finish a project for a deadline. The project manager is tasked with the difficult responsibility of planning, organizing, and making complex decisions for the project to be successfully executed. Throughout the project, uncertainties can have a positive or negative effect on the project's scope, schedule, or cost. Creating a project schedule using software such as Microsoft Project allows the project manager to track the completed tasks, the tasks still required to be finished, and the responsible party for each task. The importance a project schedule plays in the overall success of a project is widely accepted by project managers within the industry (Jian-wen and Xing-xia 2009). A high level of schedule uncertainty is caused by the materials management and resource allocation process resulting in the potential for delays to the final completion date. Without the development of a risk mitigation plan, the project will likely experience delays causing the project to run over budget or miss the final deadline.

1.2. Motivation for Study

Materials management and resource allocation make up a large overall portion of the financial outcome of a project since any delays can cause the project to run over budget. There have been several studies conducted by the Construction Industry Institute (CII) showing how materials and equipment make up 50-60% of the projects final total cost (Caldas, et al. 2012). With nearly half of the project cost attributed to materials, companies are starting to understand the benefits of using a materials management system. There are several commercially available software packages, such as Oracle Primavera and Microsoft Project, that are attempting to help the project

manager properly schedule projects and allocate resources; however, because each project is different, it is difficult to accurately predict every potential problem using the software tool.

Mulva et al. (2016) determined that 60% of the projects reviewed either lost money or did not make a profit further suggesting the need for a proper resource allocation software designed specifically for the construction industry. With over half of the projects that companies work on breaking even or losing money, the importance of efficiently utilizing the project's resources is highlighted. Because the project bidding process is so competitive between companies, the profit margins on each project are something cost estimators must use to decide between losing a project to a competitor who might underbid them, or competitively pricing a project, which will reduce the potential profit. Often engineering, procurement, and construction (EPC) firms build in a reserve to account for unforeseen circumstances, thus mitigating their risk.

The *Modern Management Systems* report of the Business Roundtable indicates that a little more than 6% of all labor costs on construction projects can be saved if the materials and equipment were available when the task was scheduled to be completed (Caldas, et al. 2012). Because construction projects can cost millions of dollars, the potential figure that could be saved by a general contractor could determine if a project is profitable or not. Companies must become more efficient in how they allocate their resources, allowing them to price projects that will compete with other companies' bids while returning a higher profit.

A review of the literature indicates there has been research conducted in several areas of the construction industry, including materials management, resource allocation, scheduling methods, and Monte Carlo simulation to assess the impacts of uncertainties which could cause delays. Several research teams from the CII are looking at ways to improve multiple aspects of the construction process such as the global procurement (Budler, et al. 2010), benchmarking

(Morrow, et al. 2013), performance assessments (Mulva and Oliveira 2014), and materials management teams (Caldas, et al. 2012). There are other researchers Vukomanovic, Radujkovic, and Dolacek Alduck (2012) and Wale et al. (2015) who examine the impacts of how software such as Microsoft Project or Oracle Primavera can impact the outcome of project schedules. As many construction companies work on multiple projects concurrently, research teams of Faris and Patterson (2007) and Touran, Baabak, and Minchin Jr. (2015), examine how to improve the portfolio management process and understand how each project affects other projects. The literature review did not discover any research being conducted specifically regarding the delays caused through the resource allocation process, which cause construction projects to fall behind schedule.

1.3. Problem Statement

The essential question for this research is: Can a project manager accurately predict uncertainties associated with the resource allocation process causing delays within a project schedule prior to the start of a construction project? Specifically, this research has a primary objective to develop an analytical model to determine potential resource allocation delays using Monte Carlo simulation with the following steps:

- Conduct an in-depth literature review of the materials management and resource allocation research being conducted in the construction industry;
- Develop a model with which a project manager with little to no risk management experience can quickly and accurately assign probabilities and potential delay times;
- Interview subject matter experts (SMEs) to gather insight into the construction industry and potential usefulness of the model;

- Define each of the three major resource categories used for each task namely equipment, materials, and labor;
- Verify the model is working properly by replicating the results from a previous project;
- Perform an in-depth case study to demonstrate the effectiveness of the model by comparing the results to a previously completed project to perform validation of the model; and
- Identify areas for future work so the research can be expanded.

An in-depth case study will be conducted to show the potential effectiveness of a model used to predict the impact of the resource allocation uncertainties that construction projects experience. This will allow the project manager to better predict certain delays so intervening steps can be taken to reduce the negative effects of delays on the overall deadline of the project.

1.4. Report Layout and Limitations

As previously stated, the research conducted in this thesis is an in-depth case study to show a proof of concept of the model. Further analysis will be needed to draw any final general conclusions, as there are not enough results with which to validate the model from multiple projects with similar characteristics. The model will also need to be extended to multiple projects within a portfolio to examine the effectiveness of the model across the company as a whole.

Chapter 2 of this thesis will present a review of the literature including a look at the general body of knowledge (BOK) relating to materials management, resource allocation, scheduling methods, portfolio management, risk management, and Monte Carlo simulation inside the construction industry. Next, Chapter 3 describes the methodology and approach used to develop the deliverables of the study, as well as the tools for data collection and data analysis. Chapter 4 presents the results from the outputs of the Monte Carlo simulation and critical path

calculations used to determine the outcome of the project. Lastly, Chapter 5 will include the conclusions and results from the model outputs when compared to the actual results from the project.

2. Literature Review

2.1. Introduction

The literature review consists of multiple research areas within the construction industry from both researchers at large and research performed through the Construction Industry Institute (CII), a research and development center focusing on capital projects within the construction industry. The literature review focuses on two major areas within the industry: the current methods of the industry, and the need for improvement across the industry. Research was conducted in materials management, resource allocation, scheduling methods, portfolio management, risk management, and Monte Carlo simulation, all of which play a major role in the outcome of a construction project.

2.2. Materials Management

The construction industry is susceptible to delays within the project schedule due to several factors including the improper management of materials. The materials management focuses on the planning, identification, procurement, receiving, storage, and distribution of the materials used throughout a project (Ramaraj 2014). Effective materials management allows the project manager to have the proper resources needed to complete a task available at the right time and the right place. Because materials management plays such a large role in the construction industry, there has been extensive research conducted by several research teams. The CII has developed research teams such as the Global Procurement and Materials Management Research Team (Budler, et al. 2010) , the Materials Management Implementation Team (Caldas, et al.

2012), and the Performance Assessment Program (S. Mulva, et al. 2016) to understand the effects of improper materials management and the way it impacts the project outcomes. Because materials management and resource allocation are branches of resource management, the same importance applies to the entire resource management process as well.

The CII primary research team of Mulva, Oliveira, and Yun (2016) conducted a materials management study where companies were asked a series of questions to assess the perception of their team members performance within each phase of the project. The responses were then scored from 0 to 5, with the lowest score representing negative perceptions for all the questions relating to each phase. The materials management portion presented a low average score on a company's performance in the engineering phase of the project contributing to a higher cost financially and delays added to the project schedule deadline. This indicates an opportunity for improvement for the entire industry. This CII study has caused companies throughout the construction industry to consider new programs designed for the current materials management systems to improve components critical to the success of a project. Materials management programs are designed to help reduce costs, improve productivity and overall quality, create a safer work environment, and ensure the project outcomes are completed, all of which contribute to how the general contractor and owners of the project view the outcome (Budler, et al. 2010).

For companies to fully adapt to a materials management software system implemented for all projects, there needs to be a push from company executives who see the value in changing the current operating policies by incorporating them within the overall strategic plan of the company. A study conducted by Budler, Caldas, and Menches (2010) that included surveying numerous owners and contractors concluded that nearly 70% of the responses from the survey indicated a materials management program was part of their corporate strategic plan for the

vision of the company. This shows the willingness of companies to adopt practices that improve the overall project management process. Without the support from executives, the construction industry would continue to fall behind other industries who are more willing to adopt new technology and embrace the technology throughout their daily practices.

Despite the recognition from the executives regarding the need to incorporate materials management programs into their corporate strategy, many of these companies still do not have such a system in place. Of the 53 companies who answered the question in the survey, 49 of these companies reported lacking these functions because they relied on other contractors such as the EPC firms to monitor the materials management process or were hired as a consultant who was not responsible for any of the materials management process (Budler, et al. 2010). Despite the recognition from leaders within companies, changing the process is difficult as it often requires a large amount of time and money.

In each of the phases within the construction industry, materials management plays an important role, ensuring the resources are allocated in an efficient manner and allowing the work to be completed on time. The research team lead by Mulva, Oliveira, and Yun (2016) conducted research into how various techniques impact the different construction project phases namely front-end planning, engineering, procurement, construction, and startup of the construction project. The study concluded that materials management was a large contributor in the front-end planning, engineering, and construction phases of a project. The study also mentioned the need for more research to be conducted regarding how the materials management system affects the construction process including all the phases, not just focusing on how it affects each phase individually (S. Mulva, et al. 2016). Because all the phases of the construction project rely on

each other, it is important to realize how the utilization of a system early on in a project can have a positive effect on phases occurring later in the project timeline.

The research team of Budler, Caldas, and Menches (2010) reported that material shortages can be identified prior to them happening with proper planning and system integration, which indicates the direction research needs to be taken. If time is spent creating a system that can accurately identify potential material shortages before the project even starts, there can be proper steps taken to minimize the potential for that situation to affect the project when the time comes. This allows the project manager to predict potential delays in the schedule and implement a strategy to prevent the project from falling behind schedule.

A research team by Caldas et al. (2012) defined materials management as a process in which materials and equipment are identified, purchased, and delivered for an intended use on a project. For this study, materials management will be defined as a process in which resources such as materials, equipment, and tools are identified, planned, purchased, delivered, and utilized to complete a project's deliverable or task. This process is extremely complex as it may require companies across the world to deliver thousands of materials to a job site at the proper moment, thus ensuring the project does not fall behind schedule (Budler, et al. 2010). Today, organizations have turned to technology to aid in the process of materials management because it is such a large and complex problem, critical to the outcome of the project.

In a survey of the construction industry conducted by Budler, Caldas, and Menches (2010), they reported that 71% of companies have an integrated computer materials management software system. The software such as Microsoft Project or Oracle Primavera aid the project manager in the entire process of materials management throughout the life of the project. As

companies continue to take on larger, more complex projects the use of a materials management software usage will only continue to grow.

2.3. Resource Allocation

Resource allocation in the construction industry is a subset of the resource management system focusing on the planning and distribution of resources. Many researchers and professional societies have developed their own definition of what a resource is, as depicted in Table 2-1.

Table 2-1: Resource Definitions

Individual/Society Name	Definition of a Resource
(Wernerfelt 1984)	Resources are anything a company uses that can be considered a strength or a weakness.
(Project Management Institute 2004)	Resources are skilled human resources such as specific disciplines, equipment, services, supplies, commodities, materials, budgets, and funds.
(Association for Project Management 2012)	Resources are needed to deliver a project, programme, or portfolio including people, machines, materials, technology, property, and anything else required to complete the task.
(Govan and Damjanovic 2016)	Resources are considered to be tangible assets such as capital, labor machinery, and natural resources, as well as intangible assets including the company brand, technology, education, and skill set.

For purposes of this research, the definition of a resource is defined as the equipment, materials, and labor used on a construction project. These were selected as they represent the three largest resource categories within the industry.

The definition of resource allocation is the scheduling of tasks and activities where resources are required to complete a task and the project manager must consider both the resource availability and time required for task (Luciaja 2013). Resource allocation is an important factor in the outcome of the project because of the number of supplies and sub-contractors the project manager must coordinate with to successfully complete a task.

A critical component of the resource allocation process is resource planning. After the project manager identifies which resources are going to be needed on a project, a plan must be developed of how to obtain and manage these resources. A research team of Nagaraju, Sivakonda, and Chaudhuri (2012) defined resource planning as a course of action for controlling and directing resources such as workers, machines, and materials in a coordinated and timely fashion to finish the project task on time and within budget. This plan of action allows the project manager to secure the resources, so they can be delivered and utilized at the correct time, allowing the project to stay on schedule. Without a plan of action, the project has a higher chance of falling behind schedule due to the lack of resources available to complete the desired tasks.

One of the most common ways for a construction firm to identify and develop a resource plan is in the development of a resource breakdown structure (RBS), which places the project resources in a hierarchical tree diagram with increasing levels of detail in lower branches of the tree. The RBS makes it easier for the project manager to conduct various techniques, such as resource leveling, to maximize the effectiveness of the resources available for a specific task. Because the RBS is created based on the work breakdown structure (WBS), resources needed for each task are included in the WBS. This ensures the project manager can plan and control the resources properly for the project. Because the RBS is broken down into specific resources for every task, the RBS can also be used to help identify any risks associated with each level in the diagram (Govan and Damnjanovic 2016).

2.4. Scheduling Methods

Schedules are built for the tasks that need to be completed for the project to be finished in a timely manner. Each task requires a certain amount of resources to finish the task within the project. This is often one of the most complex components of managing a construction project,

as the detail changes on a daily or weekly basis based on factors that the general contractor or project manager often cannot foresee. A study conducted by a CII research team surveyed general contractor companies to see how the sub-contractors who work for them affect the schedule of a project. The study determined that a majority of the contractors and project managers acknowledged they had challenges in building the schedule due to the sub-contractors' needs for each task (Budler, et al. 2010). Subcontractors are working on multiple projects just like the general contractors, so ensuring that the subcontractors have the right amount of equipment or resources available to them to finish the task is important in the overall schedule of the project.

There are some resources that are more difficult to get and will ultimately determine if specific tasks are completed on time, which makes the scheduling of a project difficult. Another factor that makes a project difficult to schedule is the precedent relationship whereby certain tasks will rely on previous tasks to be completed before they can begin. A study by Hartmann and Briskorn (2009) concluded that scarce resources and precedence relationships between tasks makes scheduling a challenge for the project manager. Because a resource allocation system relies on the schedule to know when and where the resources should be assigned, the schedule is a critical component of a project.

The schedule of a project is built from the work breakdown structure (WBS) which lays out all the tasks that need to be completed for the project. There are two commonly used ways a schedule is generated, with the most common being the activity-on-node (AON) network where each node is a specific task. The other option used is the activity-on-arc (AOA) network in which the task is placed on the arrow connecting the nodes. It is common for the project manager to use

a scheduling software package such as Microsoft Project or Oracle Primavera P6 to help manage project tasks.

Once this network is created, the project manager will be able to locate the critical path of the network using the critical path method (CPM). This method was developed by DuPont Inc. in the late 1950s and was quickly embraced by the construction industry. The CPM uses deterministic activity time estimates to help control the time and cost components of a project (Meredith, Mantel, Jr. and Shafer 2015). The critical path is the longest path between the start and finish of the entire project. Tasks not on the critical path are said to have slack or float, so if a delay occurs on these tasks not exceeding the slack time, there is no delay to the final completion date. If the delay exceeds the slack time for a task not on the critical path or if a task on the critical path is delayed, the entire project is delayed.

Another scheduling technique developed around the same time as CPM is the Program Evaluation and Review Technique (PERT). This method was developed by the United States Navy with the help of Booz Allen Hamilton and the Lockheed Corporation for the Polaris missile and submarine project. This technique focuses on the time component of a project by using probabilistic activity time estimates to help determine the probability a task can be completed (Meredith, Mantel, Jr. and Shafer 2015). To calculate the expected time of the project, the project manager must use Equation 1-1.

$$TE = \frac{(a + 4m + b)}{6} \quad \text{Equation 1-1}$$

where

TE = expected time

a = optimistic time estimate

b = pessimistic time estimate

m = most likely time estimate

The “most likely” time, m , is the mode of the statistical distribution where the project manager estimates the most likely duration a task will take to be completed. The “optimistic” time, a , is an estimate of the time required to complete the task with everything going as fast as possible where the task is finished ahead of schedule. The “pessimistic” time is an estimate of the time required to complete the task with everything going slower than expected causing a delay within the schedule. The expected time, TE , is a weighted average of a , m , and b where the weights are 1, 4, 1 respectively. This means the most likely time estimate, m , has the highest weight value while the optimistic, a , and pessimistic, b , time values are weighted equally.

Each project must deal with uncertainty or risks that affect the overall timeline and schedule of a project. According to Herroelen and Leus (2005), there are five ways to deal with uncertainty when scheduling a project: reactive scheduling, stochastic scheduling, proactive scheduling, scheduling under fuzziness, and sensitivity analysis on the schedule. The way in which a project manager schedules the project depends on the tasks that need to be completed and the resources available.

The most common uncertainty associated with a construction project deals with the resource allocation process. This type of problem is known as the resource-constrained project scheduling problem (RCPSPP) and is a specific type of scheduling problem where resources are assigned to activities with a limited capacity making the project schedule. Therefore, a project network and schedule are constrained from the capacity due to the limitations of the resources effecting the final deadline of the project schedule (Christodoulou 2017). Ideally, construction companies will not face a shortage of resources during the project; however, no project is going

to be perfect. Being able to identify potential delays or risks before they occur will help to ensure that the project to remain on schedule.

2.5. Optimization

Another technique used in the materials management process within the construction industry is optimization. Optimization is an operation research technique that solves the complex problem of allocating the available resources to various activities in a way that is most effective to the organization (Hillier and Lieberman 2010). Optimization is used to search for an optimal or best solution which can come in the form of one solution; however, it is more common for there to be multiple solutions to the problem or no solution at all. Hillier and Lieberman (2010) define an optimal solution as a feasible solution with the most favorable value of the objective function.

If a problem has multiple optimal solutions there can be infinite optimal solutions, all of which provide the same optimal value to the objective function. If there are multiple optimal solutions, what-if analysis to be conducted to determine what would happen to the optimal solution if assumptions are made about the potential outcome (Hillier and Lieberman 2010). If there is no optimal solution to a problem, it usually indicates there is no feasible solution because the constraints are too tight, and no solution can be reached.

One common technique is to create a linear programming (LP) model which uses linear mathematical functions in both the objective function and constraints. The standard form of a LP model is to have an objective with a maximizing function such as the profit; however, there are other forms a model can use such as minimizing for example the cost. The construction industry is often trying to maximize the profit associated within a project, minimize the number of delays, or maximize the number of tasks completed with the resource available making optimization a common technique used to manage materials and resource allocation.

Optimization within the materials management phase can be applied as a maximization problem with the objective on the convergence to the equiprobability distribution in the daily resource histogram (Christodoulou 2017). A more simplified way to describe optimization is that it is trying to maximize the number of tasks completed by assigning the resources available for each task in the project's schedule. It can also minimize the number of resources not being used depending on which application the project manager views applicable for the specific project. Optimization can also be used in the scheduling portion of the project, where the project manager is trying to maximize the number of tasks completed or minimize the number of overall delays throughout the project.

2.6. Risk Management

Risk management has only been recently applied to the construction industry as a point of interest to study the effects on the outcomes of projects. There has been even less research conducted on combining the risks associated with resource management to predict potential issues further in the schedule of the project.

A study performed in 2016 analyzed various impacts construction projects have on achieving the project's scope and concluded there is a lack of general framework for assessing the risk's impact on the project's objectives (Sanchez-Cazorla, Alfalla Luque and Irimia Dieguez 2016). It is difficult for project managers with large general contracting firms to assess all the risks a project might encounter. A framework or guideline developed for project managers to use to aid in assessing the risks would be useful.

Many companies consider risk management to be a critical component to the project's success. According to a report from 2016, building owners require the project manager to consider risk management throughout the project (Sanchez-Cazorla, Alfalla Luque and Irimia

Dieguez 2016). As improvements in technology continue to increase the effectiveness and speed at which companies can assess potential risks, this will continue to be an important aspect of project management as the companies see the benefits.

Risk management is a way for construction companies to reduce the setbacks for each of their projects. A study conducted by Renault and Agumba (2016) describe a risk as the probability of a loss, setback, injury, disadvantage, or destruction a project could face. Not all risks have a negative impact on the project. Some risks, like the development of a new technology, have the potential to speed up the process or reduce the initial project cost. Although there are positive risks, most project managers tend to believe most risks have a negative impact on a project. Faris and Patterson (2007) identify three types of risk a project manager must oversee including the process of identifying and quantifying the risk, the development of a risk response, and the control or implementation of the risk response. Risk can either be internal, which the project manager can control, or the risk can be external, which the project manager has little to no control over (Faris and Patterson 2007). Most risks associated with a project are going to be external, so developing a detailed risk management tool is crucial to the success of a project.

A detailed risk management plan needs to incorporate several key components, such as the project's scope, financial budget, schedule, resource management plan, work breakdown structure, and project communications plan (Faris and Patterson 2007). Once the risk management plan is created, risk analysis needs to be performed to analyze potential setbacks associated with the project. For the construction industry, this usually includes the following steps: risk identification, risk mapping with the probability of occurrence versus potential severity, probabilistic risk analysis and evaluation, and the development of alternative risk

mitigation strategies to reduce the effects a risk has on the outcome of the project (Govan and Damjanovic 2016). Schatteman et al (2008) reported that the identification phase of the process is the most important to the overall success of a project. Once a risk has been identified it can then be managed by taking the necessary steps to mitigate it to reduce the impact on the project.

Before a mitigation strategy can be developed, the project manager must analyze the identified risks using either a qualitative or quantitative method. The qualitative method is easier to implement because it uses a descriptive scale; for example, a scale with low to high ranking system. This requires less time up front for the project manager because it is not necessary to have every probability for each risk; however, this technique is less accurate than the quantitative method. The quantitative method shows each risk's impact, and probability is estimated based on a statistical analysis from the SMEs or derived from a model. This method takes a significant amount of time to develop, therefore, it is less commonly used throughout the construction industry. It is important to remember that it is impossible for SMEs and the project manager to predict every potential risk associated with a project. For example, some risks are extremely low or rare although they have a significant impact on the outcome.

2.7. Monte Carlo Simulation

A risk management analysis technique commonly used to determine the effects of various risks is Monte Carlo simulation. There are several types of Monte Carlo simulation the project manager can use such as a probability-impact table, what-if analysis, or sensitivity analysis, all of which are used to help make a decision when there is uncertainty. These techniques are used to address “what if. . .?” types of questions that arise from parameter changes (Herroelen and Leus 2005).

Monte Carlo simulation is a technique that combines historical data with inputs from SMEs to assign a weight or probability of the occurrence of a certain risk throughout a project. This technique examines various scenarios before the first task is even started, allowing the project manager to determine potential setbacks before the project occurs, making adjustments as the project progresses towards completion (Faris and Patterson 2007).

2.8. Portfolio Management

A project manager must also understand how the materials management, resource allocation, and risk management of one project can impact the outcomes of other projects within a general contracting firm's portfolio, called the project portfolio management (PPM). Because companies are working on multiple projects concurrently, the need for a proper materials management or resource management system is even more crucial to the success of a system. A study conducted by PM Solutions (2013) concluded that one of the biggest PPM pain points for a project manager is resource management. As more research is conducted in this area, specific software designed for the construction industry can help to reduce this pain.

Because companies are working on multiple projects concurrently, a large amount of information about the resources is required. Companies need to have a system in place to know exactly what resources they have available to them as well as track the location of the materials to ensure they are in the correct place at the right time. According to PM Solutions (2013), there are five PPM Challenges that plague the construction industry; however, only one applies to the resource allocation process which is: #4: Lack of information on resources. A company first needs to recognize what resources they have available to them before they can subsequently track, allocate, or purchase additional resources needed to effectively manage their projects.

Not only are companies managing multiple projects at the same time, but many of these projects can be quite large. These projects tend to be known as mega-projects within the industry and often require a complex decision-making process because of the size of the financial budget and amount of resources required (Sanchez-Cazorla, Alfalla Luque and Irimia Dieguez 2016). These projects offer a unique opportunity for contracting companies to use materials management or resource allocation software because any delay in the schedule has the potential to decrease the profit margins.

Project managers also must consider how the other projects within the portfolio will affect the resources their project might need at a specific time. Because companies often have a limited amount of resources to be shared between projects in the entire portfolio, it is essential to understand that each individual project's disruptions can cause a delay in other projects within the portfolio (Schatteman, et al. 2008). A resource management tool that has the capability to be expanded to view multiple projects would provide the companies with a valuable advantage.

The general contracting companies also need to focus on developing the skills of their project managers. Resource management systems and tools are only as effective as the people that operate them, so a considerable amount of time should be used in developing the employees. A CII study conducted by Touran, Baabak and Minchin Jr. (2015) listed two portfolio management skills every project manager within the construction industry should have including: resource allocation and resource control. This research shows how it is important for companies to spend time and resources to develop their team as new systems are put in place to help improve their profit margins on the various projects companies work on simultaneously.

2.9. Microsoft Project and Oracle Primavera

Resource allocation and materials management is widely considered to be a top priority for companies managing a portfolio of projects. A study that looked at the top five priorities companies will have in the next year concluded that nearly 65% indicated that their most important priority was to improve resource planning and forecasting processes (PM Solutions 2013). There are currently commercially available software or tools that examine various components of a construction project; however, there lacks a state-of-the-art project designed specifically for the industry as a whole. A report studying the impact of resource management programs' effects on the outcomes of a project concluded that a state-of-the-art resource management software is essential to the successful outcome of a project (Nagaraju, Sivakonda and Chaudhuri 2012). A resource management software could dramatically impact a company's ability to complete the scope of a project within the budget and schedule provided by the owner.

There are two main project management software products commonly used in the construction industry; however, new software designed specifically for the construction industry continue to be developed. The most common software used by project managers is the Oracle Primavera P6, with Microsoft Project coming in second. A study conducted in 2012 showed that in the United States nearly 64% of the construction companies use Oracle Primavera as their primary scheduling software while just over 20% use Microsoft Project (Vukomanovic, Radujkovic and Dolacek Alduk 2012). Construction companies typically need a portfolio project management software that can manage multiple projects at the same time, thus there is a strong preference for Oracle Primavera. If a project manager prefers a simple multipurpose software then the lower cost Microsoft Project should be used (Vukomanovic, Radujkovic and Dolacek Alduk 2012).

There are several different views on the usefulness of Microsoft Project within the construction industry. Some, such as Winter and Evrenosoglu (2011), believe there are few differences in the operations of Microsoft Project and Oracle Primavera so either can be used on all projects. Other researchers such as Vukomanovic, Radujkovic, and Dolacek Alduk (2012) concluded that Microsoft Project is not as widely adopted as the Primavera software because Microsoft Project has never completely aligned with the needs of the construction industry's processes and procedures. Plus, as stated earlier, Oracle Primavera P6 has the ability to effectively manage a portfolio of projects.

Although Microsoft Project and Oracle Primavera are the two most used project management software products, there are other software tools developed which focus on the unique processes and procedures of the industry. Project management software such as Buildertrend, CoConstruct, Procore, RedTeam, and PlanGrid are starting to gain traction as companies see the benefits of using a construction specific project management tool. The capabilities of the new software packages are similar to those of Oracle Primavera and Microsoft Project; however, there are some advantages of the new software such as capturing and identifying images on the jobsite, updating project drawings as changes occur, and incorporating external programs such as Intuit for accounting and tax purposes. If Microsoft Project and Oracle Primavera fail to incorporate the needs of the construction industry, their use will start to decline as other project management software products become more attractive to the industry.

2.10. Conclusion

The literature is in agreement that improper resource allocation with the materials management system plays a large role, both financially and in the overall success of the project. As

technology continues to develop in other industries, the construction industry needs to adopt tools and software to improve recognition and efficiency within the resource allocation process.

Next, Chapter 3 describes the methodology and approach used to develop deliverables of this research study as well as the tools used for the data collection and data analysis.

3. Methodology

3.1. Introduction

An analytical modeling tool is developed to estimate the number of delays within the resource allocation process prior to the start of a construction project. Utilizing this tool, the project manager will be able to see if the project's critical path shifts due to the new delays and understand where the delays occur in each task. To show the complexity of the project, an influence diagram will be created to show the complexity of this type of problem within the construction industry. The model will be created in three phases with a combination of Microsoft Project, Microsoft Excel, and an Excel add-in, Palisade @Risk. The model is built on an actual completed project, with the results compared to the actual outcome of the project to determine the effectiveness of the model to predict resource allocation delays prior to the start of the project.

3.2. Influence Diagram

Influence diagrams, or relevancy diagrams, are useful to the project manager because they provide a visual representation of the decision process. Tani and Parnell (2013) describe an influence diagram as a graphical or visual representation of the decision being made. These diagrams help the project manager define the frame of the decision to be made, identify the inputs, uncertainties, and decisions included in the model, and communicate the structure of the

model to the project manager as well as other stakeholders such as the owner of the building (Buede 2005).

Each influence diagram shape holds a specific meaning. The common symbols of an influence diagram are depicted in Figure 3-1.

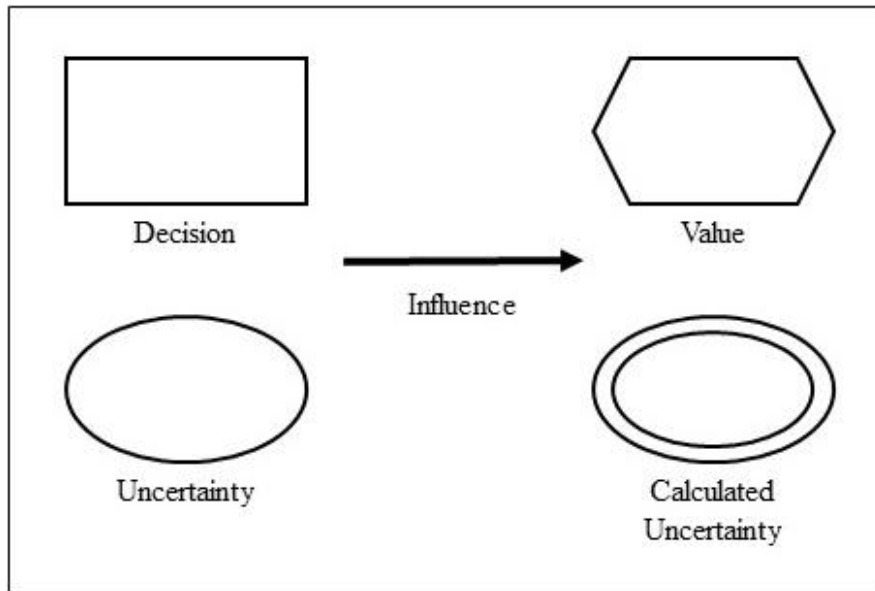


Figure 3-1: Shape Elements of an Influence Diagram

A *rectangle* is representative of a decision which the project manager will be required to make from a specified group of alternatives. There can either be one main decision or multiple decisions within an influence diagram depending on the complexity of the problem.

An *oval* is representative of an uncertainty, which can be either continuous or discrete. A continuous uncertainty is a random variable with a value of any real number within a specified range of potential outcomes, while a discrete uncertainty is a random variable with a value of any countable subset of real numbers such as a set of integers within a specified range (Tani and Parnell 2013). Another component of an uncertainty is whether it is a scalar or a vector. The difference between the two is a scalar which is the uncertainty one describes by a single number

value while a vector describes the uncertain factor values across a time series (Tani and Parnell 2013).

A *double oval* is representative of a calculated uncertainty. A calculated uncertainty is calculated by other uncertain factors (decisions, uncertainties, constants) throughout the influence diagram. If these other factors are known, the calculated uncertainty would also be known.

An *octagon* is representative of a value measure. A value measure is a decision criterion, which is a measure that is either maximized or minimized based on the desired outcome the project manager is looking to achieve with the model. In single objective decision analysis, the value measure often is the net present value of future cashflows. Some influence diagrams have multiple value measures depending on the desired project outcomes.

An *arrow* represents a relationship between two of the other elements located within the influence diagram. An arrow between two uncertainty nodes indicates there is a probabilistic dependence between the two connected elements. The direction of the arrow indicates the order of conditionality where the probability of an element at the head of the arrow is conditional on the outcome of the element at the base of arrow. The placement of an arrow between two elements must be well thought out because the direction of the arrow is important in the understanding of the problem and collection of data.

3.3. Interviews of Subject Matter Experts (SME)

Interviews of SMEs allows a researcher to understand the current processes and insight into criteria a new model should include in order to be adopted by project managers throughout the industry. Understanding precisely what the stakeholders or project managers think by gathering their insights is often considered the most important component in the development of a model.

Without establishing the need and want of a new analytical modeling tool, the analysis could be considered useless by the industry because it is not what they are looking to use. To gain the most insight, the interviews should be conducted during various stages of the research with individuals throughout the industry, at all levels of the organization, and with various levels of expertise.

In this research, interviews were conducted with SMEs to understand the need of a model to be developed to predict the potential delays within the construction industry. The types of questions are broken up into two sections: demographic information and project information. The demographic questions are used to document the credentials of the SME, while the project questions discuss the current methods used at their companies, their thoughts on the construction industry's willingness to adopt new tools, and their thoughts on the model developed for this thesis. By agreeing to answer the questions, the interviewees implied their consent to participate in this research. The implied consent agreement and a complete list of the interview questions can be found in Appendix A and Appendix B, respectively.

3.4. Data Collection

Along with the interviews of the SMEs, each was asked if they could provide information on a project either they themselves had worked on, or a project in which they had contact information for a project manager. The type of project data needed for analysis to be conducted includes a complete list of project schedules and a follow-up interview for the validation of the model. Along with these two things, a work breakdown structure (WBS), a resource breakdown structure (RBS), email correspondence regarding potential delays, the outcome of the project, and contact information for members on the project team were provided. With this information,

detailed analysis can be conducted to determine the potential effectiveness of the analytical model.

3.5. Data Analysis and Model Development

For data analysis to be conducted, a model was developed for the project manager to use to input probabilities of delays for each task within a schedule. This allowed the delays calculated by the model to be exported into Microsoft Project to determine if the critical path for the project changed after the delays were added. The outcome of the analysis was compared to the actual result of the project discussed with the project manager for the project to see if the model was accurate in the prediction of the delays. This allowed for the hypothesis to be analyzed to determine the success of the research.

The model used for the analysis was built in three phases using a combination of three software tools: Microsoft Project, Microsoft Excel, and an Excel add-in Palisade @Risk. The first phase in the model development was to recreate the original project schedule using Microsoft Project. Once the tasks were added, the critical path of the project was calculated using the Critical Path Method (CPM). The critical path is the longest path of time duration through the network or schedule, which is the shortest amount of time in which the project can be completed (Project Assistants 2016). If a delay occurs on the critical path of the project, the overall duration of the project will be extended.

The second phase of the model development was to take the task number, duration, and task name from Microsoft Project and transfer the information into the model developed using Microsoft Excel. This allows the project manager to input the uncertainty probabilities needed to conduct the Monte Carlo Simulation using the Palisade's @Risk software to determine the length of delays. One advantage of using the @Risk software is that a detailed statistical report and

graphical outputs are generated for further analysis that the project manager can use to assess the potential delays associated with the project schedule. Because the analysis should be conducted prior to the start of the construction project, it allows the project manager time to create a plan to ensure on time project completion.

The last phase of the model is transferring the delay outputs into the original project schedule, so analysis can be conducted. The new critical path is compared to the original critical path to see if the delays changed the path of the project and to determine how many days the project has been extended. The project was compared to the final schedule of the project received from the project manager to compare the model results versus the real-life project outcome.

Prior to the development of the model, a meta influence diagram was created for a visual representation of the complexity of the resource allocation problem at hand. The use of Microsoft Project, Microsoft Excel, and Palisade's @Risk was used to develop a model to conduct an in-depth analysis of a case study. This model was used to analyze the predicted delays versus the actual outcome of the project to determine if an analytical model was effective in determining delays prior to the start of a construction project.

Next, Chapter 4 will discuss the results from the development of the influence diagram, the analytical model to predict the delays, and the results from the data analysis when compared to the actual results of the project.

4. Results

4.1. Introduction

This chapter outlines the outcomes of this research project. The final version of the meta influence diagram, interview questions and results from interviewing the SMEs, a description of the project, the development of the analytical model, and verification and validation are included.

4.2. Influence Diagram

Shown below in Figure 4-1 is the final influence diagram for this research. This shows the complexity of creating a model to predict the resource allocation scheduling delays within the construction industry. This type of influence diagrams is known as a “meta” diagram because it shows a detailed overview of the type of problem rather than showing individual inputs and outputs for the specifics of the problem. The final value measure of the influence diagram allows one to minimize the change in the critical path of the schedule to assess if the delays affect the duration of the project.

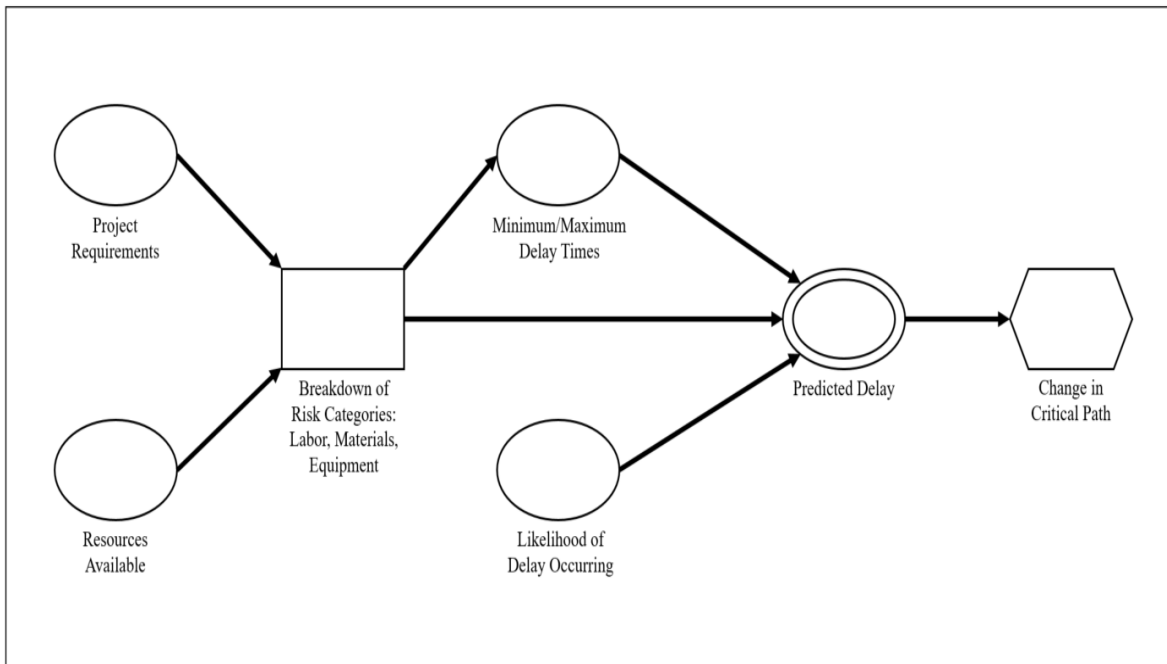


Figure 4-1: Influence Diagram for this Research

A detailed breakdown of each element within the influence diagram has been created in Table 4-1 to provide further explanation of each of these elements.

Table 4-1: Detailed Description of Influence Diagram

Name	Type	Description
Project Requirements	Uncertainty	Detailed project documents created by the owner, general contractor, and project manager. Ex: schedule, scope, work breakdown structure, resource breakdown schedule, drawings, and contract agreements
Resources Available	Uncertainty	Resources the general contractor and project manager have available for the specific project. Ex: list of subcontractors, shared resources, and contact information for material suppliers to order supplies
Breakdown of Risk Categories: Labor, Materials, and Equipment	Decision	The project manager must decide how much of each of the resource categories (labor, materials, and equipment) are needed for each task. Ex: Labor: Assigning subcontractors, number of workers, and the complication of each task Materials: Lumber, steel, cement, piping, drywall, and screws Equipment: Rental equipment, cranes, scissor lift, forklift, and bobcat
Minimum/Maximum Delay Times	Uncertainty	The estimated maximum and minimum delay times for each task in days. A negative time means the project will be completed faster than expected while a positive time means a delay occurs. Ex: Minimum – -1 days, Maximum – 15 days
Likelihood of Delay Occurring	Uncertainty	The estimated likelihood of a delay occurring. This is usually based on the project manager’s experience with delays for each task. Ex: Event Occurs – 50%, 65%, 80%
Predicted Delay	Calculated Uncertainty	The predicted delay for each task, calculated from the likelihood of the delay occurring and the minimum / maximum delay times. Ex: Total Delay - 3 days

Table 4-1 (Cont.)

Name	Type	Description
Minimize the Change in Critical Path	Value Measure	Input the delays for each task or activity within the original project schedule using the critical path method to determine if the critical path changes. Ex: Task 1 -> Task 3 -> Task 6 -> Task 8 -> Task 9 -> Task 10

4.3. Industry Interviews of Subject Matter Experts

Prior to the development of the analytical model used for this research, an interview was conducted with each of five SMEs with various job titles and levels of experience within the construction industry. Prior to each interview, an email was sent containing an implied consent form and the list of the questions that would be asked to give the SME time to prepare for each question. A copy of the implied consent form and a complete list of questions can be found in Appendix A and Appendix B, respectively.

The interview questions were divided into two sections, demographic information and project related information. The demographic questions asked how long the SME has been in the industry, their current title, the type of industries they have experience in, and the current size for both total cost and length of project. A summary of the demographic information collected from the five SME interviews can be found in Table 4-2.

Table 4-2: Summary of the Demographic Information from Interviews

Interview Question	SME #1	SME #2	SME #3	SME #4	SME #5
Experience in Industry?	45 years	30 years	2 years	15 years	36 years
Time at Current Position?	45 years	10 years	1.5 years	6 years	30 years
Current Job Title?	Owner of a General Contracting Firm	Senior IT Project Manager	Assistant Project Manager	Director of Energy Services – Building Services	Vice President of Pre-Construction
Type of Industry for Projects Working On?	Residential, Multi-Family, and Single-Family.	Commercial, Warehouse, Financial, Engineering, and Retail	Healthcare, Warehouse, Manufacturing, and Residential	Healthcare, Commercial, Educational, Research Centers, and Government Buildings	Gaming, Hospitality, and Sports/Arenas
Size of Current Project/s in Total Cost and Project Length?	\$5,000,000 and 3.5 Years	\$200,000,000 and 2 years	\$100,000,000 and 2.5 years	\$170,000,000 and 2 years	\$800,000,000 and 4 years

Combined, the five SME’s have 128 years of experience with job titles ranging from Assistant Project Manager, Vice President of Pre-Construction, and Owner of a General Contracting firm. This allows input from all experience levels to show various approaches to developing an analytical model from all levels within a general contracting firm. The SMEs have experience working in various industries such as residential, commercial, warehouse, retail, healthcare, manufacturing, gaming, hospitality, government buildings, and sports-arenas. The total cost of all the current projects is \$1,275,000,000, ranging from medium sized projects (\$2,500,000-\$10,000,000) to mega projects (>\$750,000,000).

In the second portion of the interview, the SME answered questions related to current methods used at their companies to manage projects. Some questions included how risk management for resource allocation is currently being performed, the types of risks they manage, how comfortable they are identifying and assigning risk probabilities, the best procedure for identifying risks (crucial risks per task or an aggregate approach), satisfaction with current techniques, usefulness of this study to their current company, and their likelihood of using this analytical modeling tool on future projects. A detailed summary of the project information collected from the SME interviews can be found in Table 4-3.

Table 4-3: Summary of the Project Information from Interviews

Interview Question	SME #1	SME #2	SME #3	SME #4	SME #5
Current Risk Management for Resource Allocation Method?	Experience of Project Manager	Fundamentally using Microsoft Excel	Microsoft Excel, senior leaders in each division	Experience of Project Manager	Oracle Primavera P6
Type of Risks Managed?	Personnel performance, job safety, and jobsite security	Mostly material risks, logistics, and job safety	Personnel shortages from subcontractors, injures, and not disrupt facility use	Resource management and personnel shortages	Financial, materials
Comfort Level with Identifying and Assigning Risk Probabilities?	3/10	7/10	6/10	7/10	8/10
How Should Risks be Broken Into (Crucial Risk/Task or Aggregate Approach)	Internal – Aggregate Approach External - Crucial Risk/Task	Aggregate Approach	Aggregate Approach	Crucial Risk/Task	Aggregate Approach

Table 4-3 (Cont.)

Interview Question	SME #1	SME #2	SME #3	SME #4	SME #5
Are You Satisfied with Your Current Approach?	Yes	No	Yes	No	No
How Useful was this Study for Your Current Company?	Useful when combined with project manager experience	Useful because it is scalable and applicable to all types of areas	Could be a major advantage in scheduling	Somewhat Useful	Useful because it makes you think about different risks
Would You Consider Using this Model/Tool in the Future?	Yes	Yes	Yes	No	Yes

From the SME responses, it is clear that the model needs to be easy to use because, despite their experience in the industry, their comfort level with identifying and assigning probabilities to risks is relatively low to medium (ranging from 3-8). Combining the experience of the project manager with an analytical modeling tool, similar to the one developed in this research, could result in valuable insight gained by the project manager, leading to a competitive edge. The SMEs interviewed for this research agreed there is potential to improve the current risk management process within their companies.

4.4. Data Collection

Prior to the development of this analytical model, a way to validate the model’s outcomes was needed to prove it is working properly. During the interviews with the SMEs, each was asked if they could provide a completed project with the required information to conduct analysis. This included a project schedule and contact information for the project manager, so a follow-up

validation interview could be conducted to ensure the outcome from the analytical model. After multiple attempts to locate a project meeting the requirements for analysis across the five SMEs, only one useable project was provided. The project was the renovation of a historic brewery on the island of Hawaii. The new tenants renovated the brewery to convert the building into office spaces for their employees. The original project schedule from 06/06/13 can be found in Appendix E, although it has poor resolution and is difficult to read. For this reason, the image has been recreated in Microsoft Project and the first 29 tasks can be found in Figure 4-2.

The building consists of five floors and approximately 11,738 square feet. The original timeline for the project was 245 working days or just over 11 months. The original schedule from 06/06/13 was first recreated using Microsoft Project to ensure the inputs for the analytical model were correct. The schedule consists of 71 tasks beginning on 05/29/13 and ending on 05/06/14. Figure 4-2 depicts a recreation of the project schedule (only the first 29 tasks are shown) with the critical tasks highlighted in yellow and a Gantt Chart showing a visual representation of the schedule.

	Task Mode	Outline Number	Task Name	Duration	Start	Finish	Predecessors	Critical
1	★	1	Project Duration	245 days	Wed 5/29/13	Tue 5/6/14		Yes
2	★	2	Mobilize @ Laydown	3 days	Wed 5/29/13	Fri 5/31/13		No
3	★	3	Mobilize @ Job Site	5 days	Thu 6/6/13	Wed 6/12/13		No
4	→	4	Set up perimeter scaffold and barrier	4 days	Thu 6/6/13	Tue 6/11/13	3SS	No
5	→	5	Elevator Dismatle by Otis	10 days	Mon 6/10/13	Fri 6/21/13	3SS+2 days	No
6	→	6	Electrical Disconnect and Drop	5 days	Mon 6/10/13	Fri 6/14/13	3SS+2 days	No
7	→	7	Set up Temp Power	1 day	Mon 6/10/13	Mon 6/10/13	6SS	No
8	→	8	Mechanical Disconnect and Drop	5 days	Mon 6/10/13	Fri 6/14/13	6SS	No
9	★	9	Begin Project Demo	61 days	Thu 6/6/13	Thu 8/29/13	3SS	No
10	→	10	Remove Metal Gates	1 day	Thu 6/6/13	Thu 6/6/13	3SS	Yes
11	→	11	Protect Pavers/Courtyard Brick	1 day	Thu 6/6/13	Thu 6/6/13	10SS	No
12	→	12	Remove 2nd Floor Windows @ Chute	1 day	Thu 6/6/13	Thu 6/6/13	10SS	Yes
13	→	13	Remove Ceiling (STO) @ Interior Courtyard	1 day	Fri 6/7/13	Fri 6/7/13	12	Yes
14	→	14	Install Handrail @ Roof	1 day	Fri 6/7/13	Fri 6/7/13	13SS	No
15	→	15	Open Trash Chute @ Roof	1 day	Fri 6/7/13	Fri 6/7/13	13SS	No
16	→	16	Install Temp Cover for Roof	1 day	Fri 6/7/13	Fri 6/7/13	13SS	Yes
17	→	17	Install 5th Floor Handrail	1 day	Mon 6/10/13	Mon 6/10/13	16	Yes
18	→	18	Open Trash Chute @ 5th Floor	1 day	Mon 6/10/13	Mon 6/10/13	17SS	Yes
19	→	19	Install 4th Floor Handrails	1 day	Tue 6/11/13	Tue 6/11/13	18	Yes
20	→	20	Open Trash Chute @ 4th Floor	1 day	Tue 6/11/13	Tue 6/11/13	19SS	Yes
21	→	21	Install 3rd Floor Handrails	1 day	Wed 6/12/13	Wed 6/12/13	20	Yes
22	→	22	Open Trash Chute @ 3rd Floor	1 day	Wed 6/12/13	Wed 6/12/13	21SS	Yes
23	→	23	Soft Demo Level 5	3 days	Thu 6/13/13	Mon 6/17/13	22	Yes
24	→	24	Soft Demo Level 4	3 days	Fri 6/14/13	Tue 6/18/13	23SS+1 day	Yes
25	→	25	Soft Demo Level 3	10 days	Mon 6/17/13	Fri 6/28/13	24SS+1 day	Yes
26	→	26	Soft Demo Level 2	10 days	Thu 6/20/13	Wed 7/3/13	25SS+3 days	Yes
27	→	27	Shore Stairways	1 day	Thu 7/4/13	Thu 7/4/13	26	Yes
28	→	28	Install Protection @ Windows	1 day	Thu 7/4/13	Thu 7/4/13	27SS	Yes
29	→	29	Dismantle Roof Units and Accessories	10 days	Fri 7/5/13	Thu 7/18/13	28	Yes

Figure 4-2: Original Project Schedule in Microsoft Project (Tasks 1 – 29)

An advantage a project manager has in using a scheduling software package, such as Microsoft Project, is the program can quickly track both the completed work and remaining work. It also shows the tasks on the critical path as it automatically generates a list calculated using the Critical Path Method (CPM). Prior to inputting the original schedule into the analytical model built in Microsoft Excel, the recreated original schedule entered into Microsoft Project was compared to the actual schedule to ensure the same result was achieved. The critical path calculated by Microsoft Project on the original schedule prior to any analysis is shown in Table 4-4.

Table 4-4: Critical Path of Original Schedule

Task #	Name	Start	Finish
1	Project Duration	Wed 5/29/13	Tue 5/6/14
10	Remove Metal Gates	Thu 6/6/13	Thu 6/6/13
12	Remove 2 nd Floor Windows @ Chute	Thu 6/6/13	Thu 6/6/13
13	Remove Ceiling (STO) @ Interior Courtyard	Fri 6/7/13	Fri 6/7/13
16	Install Temp Cover for Roof	Fri 6/7/13	Fri 6/7/13
17	Install 5 th Floor Handrail	Mon 6/10/13	Mon 6/10/13
18	Open Trash Chute @ 5 th Floor	Mon 6/10/13	Mon 6/10/13
19	Install 4 th Floor Handrails	Tue 6/11/13	Tue 6/11/13
20	Open Trash Chute @ 4 th Floor	Tue 6/11/13	Tue 6/11/13
21	Install 3 rd Floor Handrails	Wed 6/12/13	Wed 6/12/13
22	Open Trash Chute @ 3 rd Floor	Wed 6/12/13	Wed 6/12/13
23	Soft Demo Level 5	Thu 6/13/13	Mon 6/17/13
24	Soft Demo Level 4	Fri 6/14/13	Tue 6/18/13
25	Soft Demo Level 3	Mon 6/17/13	Fri 6/28/13
26	Soft Demo Level 2	Thu 6/20/13	Wed 7/3/13
27	Shore Stairways	Thu 7/4/13	Thu 7/4/13
28	Install Protection @ Windows	Thu 7/4/13	Thu 7/4/13
29	Dismantle Roof Units and Accessories	Fri 7/5/13	Thu 7/18/13
30	Demo Roof Structure	Fri 7/12/13	Thu 7/18/13
31	Demo 5 th Structure	Fri 7/19/13	Thu 7/25/13
32	Demo 4 th Structure	Fri 7/26/13	Thu 8/1/13
33	Demo 3 rd Structure	Fri 8/2/13	Thu 8/8/13
34	Demo 2 nd Structure	Fri 8/9/13	Thu 8/15/13
35	Demo ALL 1 st Floor	Fri 8/16/13	8/29/13
37	Begin SS Framing Level 2	Fri 8/30/13	Fri 9/6/13
40	Install SS Framing Level 3	Thu 9/12/13	Thu 9/19/13
42	Install SS Framing Level 4	Wed 9/25/13	Wed 10/2/13
43	Install Metal Deck Level 4	Thu 10/3/13	Wed 10/9/13
44	Install SS Framing Level 5	Thu 10/17/13	Thu 10/24/13
45	Install Metal Deck Level 5	Fri 10/25/13	Thu 10/31/13
54	Rough Carpentry Framing	Fri 11/1/13	Thu 12/19/13
60	Mechanical Rough In	Fri 12/6/13	Thu 1/2/14
61	Hang Drywall, Tape and Mud	Fri 1/3/14	Thu 2/13/14
62	Install CT	Fri 2/14/14	Thu 3/13/14
66	Cabinets, Trims, Acc	Fri 3/14/14	Thu 3/27/14
67	Paint	Fri 3/28/14	Fri 5/2/14
68	Install Acoustical Ceiling	Mon 4/21/14	Fri 5/2/14
70	Punch	Mon 5/5/14	Mon 5/5/14
71	Turnover	Tue 5/6/14	Tue 5/6/14

The critical path for the original project schedule consists of 39 tasks starting on 05/29/13 with the project ending on 05/06/14. The model results estimated the project would last a total of 245 working days. This critical path calculation is used to compare the results after the analytical model analysis is completed and additional delays are added to the project schedule.

4.5. Data Analysis

The analytical model was built using Microsoft Excel with an add-in software called Palisade @Risk to run the Monte Carlo simulation. The model is built in two tabs within one Excel workbook, the first is named “Model Results” and shows the delays for each task along with the total number of delays for the entire project. The second tab is named “Risk Calculations” which is where all the analysis is conducted.

The model is built using a color-coded system to increase the user friendliness and simplify the process for the project manager to use to predict the delays. The six colors can be found in the legend located within the “Risk Calculations” tab and includes the following: yellow-gold, green, red, grey, white, and blue. The color coding system is illustrated in Figure 4-3.

Legend:
Input
Calculation
Objective
Input from MS Project
Constant
Average Number of Delays

Figure 4-3: Color-Coding System used throughout the Model

The yellow-gold color is used to represent an input where the project manager must manually enter a value into the model. There are four columns which the project manager must input

manually: the probability of the delay event occurring or “P[True]”, the minimum delay or fastest the task can be completed, the maximum delay or slowest the task can be completed, and the rows in an output table summing the total number of delays for each of the four-risk categories namely material, labor, and total delays. This allows the project manager to quickly determine which category caused the largest amount of delay. All the delays throughout the model are calculated in full days.

The other inputs used in the model require further explanation to describe how each is used by the project manager.

The first column which the project manager must manually input into the model is the probability of a delay occurring, titled “P[True].” This type of distribution is called a Discrete Bernoulli Distribution in statistics which means there are two potential outcomes for a given scenario. In this example the two choices are either true or false, meaning a delay either will or will not occur. The project manager must manually input the P[True] instead of the P[False] because an individual is more likely to give an accurate value when predicting a value with a higher expected chance of occurring. This makes sense because delays frequently occur within a construction project, so the likelihood of a delay occurring is greater than that of the event not occurring.

In the second column of the model, the project manager must input the minimum and maximum delay times that the task might experience due to the three risk aggregates for each task. This creates a triangular distribution where three values are reported: the minimum delay, the maximum delay, and the most likely delay. Since an original schedule must be developed prior to inputting the probabilities, the most likely delay, or base delay, is going to be zero because it has already been estimated by the project manager. The delay can be both negative or

positive, where a negative delay represents the task being completed ahead of schedule. A positive value for a delay indicates it will take longer for the task to be completed than originally predicted by the project manager. When giving the duration of a delay, it is easiest and fastest for a project manager to estimate the minimum and maximum number of delays for a given task. For this reason, the triangular distribution is one of the most commonly used types of distributions for Monte Carlo simulation because it is easy for the SMEs to understand and provide accurate estimates based on their experience (Palisade 2017).

The green color is used to represent a calculation which will automatically update once all the input cells have been filled. There are four columns where a calculation is performed including: (1) the probability a delay does not occur or “P[False]” in the model, (2) the statistical distribution, which is calculated for each risk aggregate or risk category within every task titled, “Event Occurrence,” (3) the statistical distribution of the average delay from the triangular distribution inputs called “Average Delay,” and (4) the total delay time for each risk aggregate named “Delay Time.” The total delay is calculated using an “if” statement where the cell checks to see if the “Event Occurrence” occurs (=1), then the “Average Delay” column is reported, otherwise the cell recalls a value of zero for no delay.

The red color is used to represent the objective of the function, which is the total delay for all the risk aggregates for each task called “Delay Time per Task.” The red color is also used to see the sum of the total delays for each risk aggregate type. The objective cells represent the output cells used in the Palisade @Risk simulation, where the project manager can analyze the detailed statistical data. One advantage to using the @Risk software is it can generate charts and diagrams which the project manager can use to see probability distribution results of the simulation, as well as tornado diagrams such as the output mean and contribution to the variance.

This allows the project manager to determine the total delay time for each task as well as to see which of the risk aggregate factors make the largest contribution to each delay.

The grey color represents an input from Microsoft Project which must be completed prior to using the analytical model for analysis. The values the project manager needs to transfer from Microsoft Project into the model include the task number, duration, and task name. The task number and task name are also inserted into the “Model Results” tab. The project manager can use the “Model Results” tab to see the total delay by risk aggregate, then transfer the information into Microsoft Project to see if there has been a change to the critical path.

The blue color represents the average from the iterations of the Monte Carlo simulations. The total average delay for each task will be transferred into Microsoft Project to determine if the critical path changes. The averages were totaled for each task to determine the number of delays per each risk category, so the project manager can determine what types of delays the project potentially can experience. The last color, white, represents a constant throughout the model that will always be the same for every task. The first column occurs under the task name with the three risk aggregates of equipment, material, and labor, as well as the total risks. The second column named “FALSE” and “TRUE” have values of = 0 and = 1, respectively. This indicates if the event does occur, or is true, then the value of one will be used and if the event does not occur then it will have a value of (0), or false. The last constant column used in the model is the base delay calculation which will have a value = 0. This is because the project manager has already estimated the duration of the event so the delay for that value would be nothing. The block copied for each task is depicted in Figure 4-4 providing a visual representation of the color system used throughout the model.

Task Number			Event Chance Calculation (Discrete/Bernoulli Distribution)				Monte Carlo Distributions	Delay Calculation (Triangular Distribution)			Monte Carlo Distributions	Delay Occurance	Objective
Task Number	Duration	Task Name	FALSE	TRUE	P[False]	P[True]	Event Occurance	Best / Fastest	Base	Worst / Slowest	Average Delay	Delay Time	Delay Time per Task
1		Task Name											
		Equipment	0	1					0				
		Material	0	1					0				
		Labor	0	1					0				
		Total											
2		Task Name											

Figure 4-4: Risk Aggregate Block for Each Task

The equipment risk aggregate consists of any potential delay occurring on the task within a project in which a tool is used. Tools include large equipment such as forklifts, cranes, skid steers, scissor lifts and excavators and dozers which the general contracting company can either own or rent for the duration of the project. The project manager must ensure the equipment is provided on time or risk the potential for the project getting behind schedule. The equipment can also include the smaller portable tools and machinery such as specialty bits, jack hammers, hammers, screw drivers, arc welders, wrenches, ladders, and extension cords. The equipment is used repeatedly throughout the construction of the building or shared between multiple projects which a company is building within its portfolio.

The material risk aggregate consists of resources which are consumed during the construction process and purchased through supply companies. The type of material depends on the type of construction, including in some instances specialty items with long delivery times and high costs to purchase. There are multiple examples of materials used on a construction site including steel, lumber, drywall, fasteners such as screws and bolts, plumbing pipes, and cement. One main difference between a material and equipment is a material is consumed and a piece of equipment is used on multiple occurrences or projects within a portfolio.

The last risk aggregate, labor, consists of the individual or groups of individuals assigned to each task. This includes the sub-contractors hired by the project manager to complete a specific task. It also incorporates any of the work being completed within the general contracting firms for which the project manager works. If a task requires a specific skill set, the potential for a delay will be larger because it is a skill for which not every foreman has the proper training or certification.

The steps a project manager will use to develop the analytical model unique to a project are summarized in Table 4-5.

Table 4-5: Steps to Build Model

Number	Description
1	Transfer the task number, duration, and task name from Microsoft Project into the model built in Microsoft Excel
2	Copy the risk aggregate block, shown previously in Figure 4-5, to each task
3	Assign the probability of a delay event occurring or column "P[True]"
4	Assign the minimum and maximum delay times for each risk aggregate
5	Insert the distribution/input using the Palisade @Risk software <ul style="list-style-type: none"> - Use a Discrete Distribution for the column titled "Monte Carlo Distributions – Event Occurrence" - Use a Triangular Distribution for the column titled "Monte Carlo Distributions – Average Delay"
6	Insert the output for the total risk aggregate for each task
7	Insert the output for each column found within the "Total Output by Resource" table found within the model
8	Run simulation 10,000 times to provide a large sample size providing a more accurate representation of real life events
9	Analyze the results
10	Transfer the delays from Microsoft Excel into Microsoft Project
11	Determine if the critical path of the project changed once the delays are added

Following these steps, the project manager will be able to determine the potential outcome of the project after considering the delays associated with the resource allocation process. The model used for the analysis in this research was validated to ensure the model was working properly and then verified by comparing the results of the analysis to the project schedule.

4.6. Model Verification

Prior to any analysis being conducted with this analytical model, the model must be verified using another project to ensure the model is working as expected. Verification is important because the model contains a large number of uncertainties and assumptions which need to be tested. To verify the model was working properly, it was tested using the analysis from the research team of Wang and Huang (2009) which used the PERT method to identify and calculate the critical path. In Table 4-6, there are three estimated durations for each activity from the Wang and Huang analysis, including the optimistic (*a*), pessimistic (*b*), and mostly likely (*m*) values.

Table 4-6: Original Estimated Duration for Each Activity

Activity (i, j)	Estimated Duration (days)		
	A	m	b
A (1, 2)	30	36	42
B (1, 3)	36	40	44
C (1, 4)	30	40	50
D (2, 5)	30	40	50
E (2, 6)	7	10	13
F (3, 6)	38	40	42
G (4, 6)	8	10	12
H (4, 7)	20	32	44
I (5, 8)	14	20	26
J (6, 8)	18	20	22
K (7, 8)	10	20	30

A visual of the project network from Table 4-6 is shown using an activity-on-arc (AOA) diagram with all three of the estimated duration values shown above each of the task names. Using the critical path (CPM) algorithm, the project's critical path is 1 – 3 – 6 – 8 or tasks B, F, and J. The path is calculated to last 100 days with a minimum duration of 92 days and a maximum duration of 108 days. The AOA from the analysis from Wang and Huang is shown in Figure 4-5.

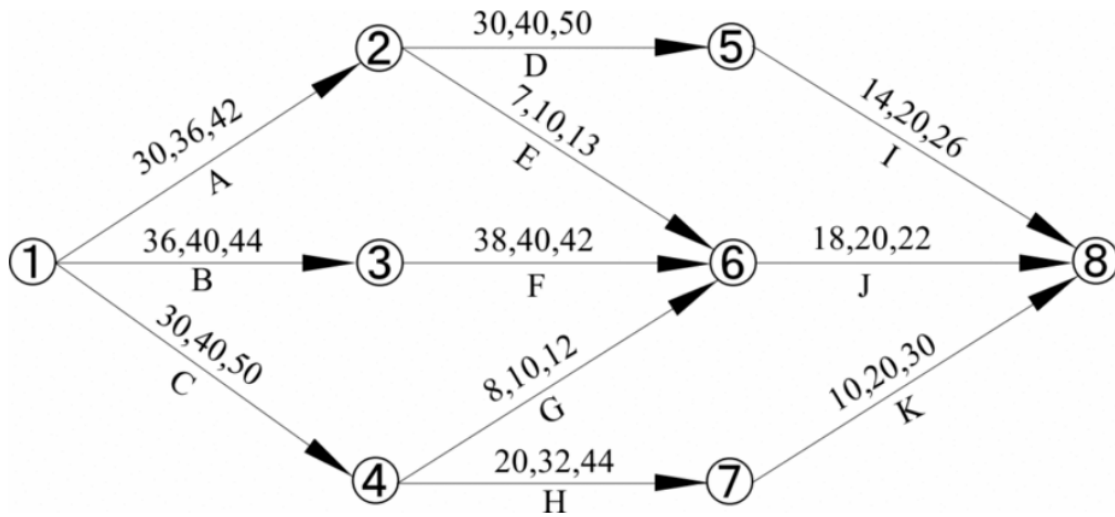


Figure 4-5: Original Activity-on-Arc (AOA) Diagram

To continue the verification of the model, the values were input into Microsoft Project. Although Wang and Huang used the PERT method to calculate the critical path, the analytical model for this thesis used the CPM algorithm. The project schedule data was provided with the start date, finish date, and duration so the CPM algorithm could be used for this research to calculate the critical path. For this reason, the most likely, or *m* values, provided by Wang and Huang were used as the estimated duration of the task to recreate the schedule in Microsoft Project. The optimistic and pessimistic values were not used to recreate the project schedule, but used later in the analysis as the delay times. Because the Wang and Huang model used the PERT method, the start and finish dates were not provided so a random initial start date was chosen. The subsequent tasks in the schedule were auto-generated in Microsoft Project based on the duration of the task and the predecessor finish date. To ensure the project data was transferred correctly with the proper predecessors, the critical path was calculated and highlighted in yellow. The project schedule in Microsoft Project is shown in Figure 4-6.

		Today								
		Dec 17, '17	Dec 24, '17	Dec 31, '17	Jan 7, '18	Jan 14, '18	Jan 21, '18	Jan 28, '18		
Start		Wed 12/13/17								
Finish										
	i	Task Mode	Outline Number	Task Name	Duration	Start	Finish	Pre	Critical	A
1		★	1	A (1,2)	36 days	Wed 12/13/17	Wed 1/31/18		No	
2		★	2	B (1,3)	40 days	Wed 12/13/17	Tue 2/6/18		Yes	
3		★	3	C (1,4)	40 days	Wed 12/13/17	Tue 2/6/18		No	
4		★	4	D (2,5)	40 days	Thu 2/1/18	Wed 3/28/18	1	No	
5		★	5	E (2,6)	10 days	Thu 2/1/18	Wed 2/14/18	1	No	
6		★	6	F (3,6)	40 days	Wed 2/7/18	Tue 4/3/18	2	Yes	
7		★	7	G (4,6)	10 days	Wed 2/7/18	Tue 2/20/18	3	No	
8		★	8	H (4,7)	32 days	Wed 2/7/18	Thu 3/22/18	3	No	
9		★	9	I (5,8)	20 days	Thu 3/29/18	Wed 4/25/18	4	No	
10		★	10	J (6,8)	20 days	Wed 4/4/18	Tue 5/1/18	5,6,7	Yes	
11		★	11	K (7,8)	20 days	Fri 3/23/18	Thu 4/19/18	8	No	

Figure 4-6: Project Schedule form Wang and Huang Project in Microsoft Project

Once the project schedule was correctly recreated within Microsoft Project, the task number and task name were transferred into the Microsoft Excel, so analysis could be conducted. The block, from Figure 4-4, containing the four largest risk categories for the construction industry namely equipment, material, labor, and total was added to each of the tasks. Because the model from Wang and Huang did not break the delays into resource categories, the equipment category was selected to represent the delay for the entire task and to ensure a delay occurred for each task the probability of the delay was assumed to be 100%. This is reasonable to assume because in the analysis from Wang and Huang only one delay was present because for every task as the project manager was required to provide an optimistic and pessimistic time value. The other two risk categories of labor and materials were assumed to have a probability of 0% because the analysis

from Wang and Huang analyzed a general delay for each task rather than separating the delays into the three resource allocation categories. This assumption ensures only one delay occurs per each task. The optimistic and pessimistic values, from Table 4-6, were used to calculate worst and best delay durations required for the project manager to input into the model. The best-case scenario or the fastest a task can be completed was calculated by subtracting the optimistic value from the most likely value. The worst-case scenario or the slowest a task can be complete is calculated in a similar way where the pessimistic value is subtracted from the most likely value. These calculations provide the delay estimations normally required to be provided by the project manager. The first five tasks of the verification analytical model are shown in Figure 4-7 for illustration purposes.

Task Number			Event Chance Calculation (Discrete/Bernoulli Distribution)				Monte Carlo Distributions	Delay Calculation (Triangular Distribution)			Monte Carlo Distributions	Delay Occurrence	Objective
Task Number	Duration	Task Name	FALSE	TRUE	P[False]	P[True]	Event Occurrence	Best / Fastest	Base	Worst / Slowest	Average Delay	Delay Time	Delay Time per Task
1	36	A (1,2)											
		Equipment	0	1	0%	100%	1	-6	0	6	0.0	0	0
		Material	0	1	100%	0%	0	0	0	0	0.0	0	0
		Labor	0	1	100%	0%	0	0	0	0	0.0	0	0
		Total										0	
2	40	B (1,3)											
		Equipment	0	1	0%	100%	1	-4	0	4	0.0	0	0
		Material	0	1	100%	0%	0	0	0	0	0.0	0	0
		Labor	0	1	100%	0%	0	0	0	0	0.0	0	0
		Total										0	
3	40	C (1,4)											
		Equipment	0	1	0%	100%	1	-10	0	10	0.0	0	0
		Material	0	1	100%	0%	0	0	0	0	0.0	0	0
		Labor	0	1	100%	0%	0	0	0	0	0.0	0	0
		Total										0	
4	40	D (2,5)											
		Equipment	0	1	0%	100%	1	-10	0	10	0.0	0	0
		Material	0	1	100%	0%	0	0	0	0	0.0	0	0
		Labor	0	1	100%	0%	0	0	0	0	0.0	0	0
		Total										0	
5	10	E (2,6)											

Figure 4-7: Verification Analytical Model

To verify the model is working properly, Monte Carlo simulation was performed to calculate the delay time for each of the tasks. The results were then compared to the analysis conducted by Wang and Huang to determine if the critical path calculations produced the same results. If the results are the same, then the analytical model used in this research will be verified. The Monte Carlo simulation was run 10,000 times, the same number of iterations as the Wang and Huang

model. The results from Monte Carlo simulation results from the analytical model used in this thesis produced the minimum, average, and maximum delays for each of the tasks within the project schedule. The delays for each of the tasks were then added together for each of the possible network paths to produce the final duration for the project. The delays can be added together because the tasks from Wang and Huang were sequential. The results for each of the five possible network paths from the Monte Carlo simulation from the analytical model developed for this research are shown Table 4-7.

Table 4-7: Project Duration Results

Possible Network Paths	Feasible Path	Duration (days)	Average Delay	Min Delay	Max Delay
1 - 2 - 5 - 8	A - D - I	96	0	-21.76	21.90
1 - 3 - 6 - 8	B - F - J	100	0	-7.93	7.89
1 - 4 - 7 - 8	C - H - K	92	0	-31.72	31.74
1 - 2 - 6 - 8	A - E - J	66	0	-10.88	10.91
1 - 4 - 6 - 8	C - G - J	70	0	-13.92	13.82

For this triangular distribution used to estimate the delay duration, the difference between the minimum and maximum delays have the same value, forming an equilateral triangle. Over the 10,000 iterations run from the Monte Carlo simulation, the results will average to the most likely value or mean which is in this project is zero. In an actual project, the likelihood that the minimum and maximum delay results will be the same difference is slim since there is a higher chance for the task to take longer than expected rather than slower than initially thought. This causes the data to be skewed towards the right or slower than expected, causing the average delay to be greater than the most likely value. Another component of the analysis conducted for this research is to determine if the delays from the Monte Carlo simulation affect the critical path of the network. The critical path from Wang and Huang’s analysis, the Microsoft Project prior to

the Monte Carlo simulation, and the Microsoft Project after the Monte Carlo simulation results were calculated and shown in Table 4-8.

Table 4-8: Critical Path Comparison

Critical Paths	
Critical path from Wang and Huang Model prior to analysis:	1 - 3 - 6 - 8
Critical path from Wang and Huang Model post analysis:	1 - 3 - 6 - 8
Critical path from Microsoft Project prior to analysis:	1 - 3 - 6 - 8
Critical path from Microsoft Project post analysis:	1 - 3 - 6 - 8
Model is Verified	

The results show the critical paths for both prior and post analysis were the same between both models. This indicated the model is working as it is intended and therefore it can be said that the model is verified. The next step was to validate the model with the assistance of a SME using data from a real project.

4.7. Model Validation

Not only does a model need to be verified to ensure it is working as intended, it also needs to be validated against real project data. This process ensures the analytical model accurately represents the data from a project, so a project manager can use it to help anticipate potential delays prior to the start of a construction project. The analytical model used in this research was developed from the data provided by the project manager. As stated previously, the project is a renovation project converting an old brewery into office spaces. The project schedule consisted of 71 tasks and was recreated using Microsoft Project. The critical path from the original project schedule was compared to the result from Microsoft Project to verify the schedules were the same. The task number, task name, and duration were then imported into Microsoft Excel, so Monte Carlo simulation could be conducted to determine the average total delay for each of the tasks.

The Monte Carlo simulation was run with 10,000 iterations to copy the number of times the number of iterations from the Wang and Huang model. The simulation was used to estimate the number of delays for each of the four risk aggregates including equipment, material, labor, and total delays. The total number of delays for each task was used to determine the effects of the delays on potentially changing the critical path. This assumes each of the delays from the three risk aggregates are independent from the other categories and have no influence on the other categories. This was assumed for simplicity purposes in developing the model, so the project manager does not have to determine the relationship or dependence between all three of the delays. This means the maximum of the equipment, material, or labor risks was used for the total delay for the individual task. The total average number of delays for each task, shown in Table 4-9, were added to the duration column in the schedule from Microsoft Project to determine if there was a change in the critical path.

Table 4-9: Model Results per Task – Total Average Delay

Task Number	Task Name	Total Average Delay (days)
1	Project Duration	
2	Mobilize @ Laydown	
3	Mobilize @ Job Site	
4	Set up perimeter scaffold and barrier	1
5	Elevator Dismantle	1
6	Electrical Disconnect	1
7	Set up Temp Power	0
8	Mechanical Disconnect and Drop	1
9	Begin Project Demo	
10	Remove Metal Gates	0
11	Protect Pavers/Courtyard Brick	0
12	Remove 2nd Floor Windows @ Chute	0
13	Remove Ceiling (STO) @ Interior Courtyard	0
14	Install Handrail @ Roof	0
15	Open Trash Chute @ Roof	0

Table 4-9 (Cont.)

Task Number	Task Name	Total Average Delay (days)
16	Install Temp Cover for Roof	0
17	Install 5th Floor Handrail	0
18	Open Trash Chute @ 5th Floor	0
19	Install 4th Floor Handrails	0
20	Open Trash Chute @ 4th Floor	0
21	Install 3rd Floor Handrails	0
22	Open Trash Chute @ 3rd Floor	0
23	Soft Demo Level 5	1
24	Soft Demo Level 4	1
25	Soft Demo Level 3	1
26	Soft Demo Level 2	1
27	Shore Stairways	0
28	Install Protection @ Windows	0
29	Dismantle Roof Units and Accessories	1
30	Demo Roof Structure	1
31	Demo 5th Structure	1
32	Demo 4th Structure	1
33	Demo 3rd Structure	1
34	Demo 2nd Structure	1
35	Demo ALL 1st Floor	2
36	Crane on-site @ Courtyard	
37	Begin SS Framing Level 2	6
38	Install SS at Elevator Shaft	5
39	Install Metal Deck Level 2	2
40	Install SS Framing Level 3	4
41	Install Metal Deck Level 3	2
42	Install SS Framing Level 4	4
43	Install Metal Deck Level 4	1
44	Install SS Framing Level 5	3
45	Install Metal Deck Level 5	2
46	Roof Framing	5
47	Membrane Roofing	5
48	Dry In	0
49	Roof Top Deck	2
50	Roof Top Screen Wall	1
51	Additional Roof Top Construction and Paint	1

Table 4-9 (Cont.)

Task Number	Task Name	Total Average Delay (days)
52	Begin Plumbing Rough In	3
53	Fire Sprinkler Rough In	3
54	Rough Carpentry Framing	4
55	Electrical Rough In	3
56	Frame Elevator Shaft	3
57	Hang and Tape Shaft	1
58	Inspection	0
59	Re-Install Elevator	4
60	Mechanical Rough In	4
61	Hang Drywall, Tape and Mud	2
62	Install CT	2
63	Install Plumbing Fixtures	2
64	Electrical Devices	1
65	Mechanical and Electrical Commission	0
66	Cabinets, Trims, Acc	1
67	Paint	1
68	Install Acoustical Ceiling	3
69	Controls	1
70	Punch	0
71	Turnover	

The bolded task names represent a group of tasks within the project schedule. The first group called “Begin Project Demo” consists of tasks 10 thru 35. The total number of delays were added together for a total of 18 days to show the total number of delays for that group. The second group called “Crane on-site @ Courtyard” consists of tasks 37 thru 47. The total number of delays from this group was 40 days. It is important to remember not all the tasks within the two groups are on the critical path so not all the delays will represent a delay to the final deadline of the project. The total average number of delays were predicted by the Monte Carlo simulation results by taking the maximum delay for each task and comparing it to the delays of the actual project from the final project schedule.

The total number of delays from each task is the maximum of the equipment, material, and labor categories. The total average delays, accounting for overlap between the categories, is the sum of the total average delays from each task. This means that if there is 1 day of delay for equipment, 2 days for material, and 3 days for labor; the total number of delays is not 6 days rather the maximum value of 3 days. The overlap for the category would be the remaining days, in this instance the 1 day of equipment and 2 days for labor delays, since they did not contribute to the final delays for the task. To calculate the total average equipment delay, the total average number of equipment delays from each task was summed together which shows the total average number of equipment delays for the entire project. The other two resource categories were calculated in a similar manner. The breakdown for the total average delay of each type of resource has been summarized in Table 4-10.

Table 4-10: Total Average Number of Delays for each Resource Category

Total Average Delays for Each Resource Type	
Total Average Equipment Delay - days	40
Total Average Material Delay - days	61
Total Average Labor Delay - days	50
Total Average Delay - days (Accounts for Overlap)	103

From the results of the Monte Carlo simulation from the analytical model, the average delays for each category were 40 days of equipment delays, 61 days of material delays, and 50 days of labor delays. Because the assumption of each of the delays are independent from each other, the maximum total average number of delays accounting for the overlap is 103 days. Although there are 103 estimated days of delays from the Monte Carlo simulation, not all the delays will cause the project’s final schedule to be pushed back because not all the delays occur on the critical path. This table allows the project manager to quickly see which resource category has the

largest number of delays to create a risk mitigation plan. For this project, the project manager will notice the largest risk aggregate is material, followed by the material delays, and equipment. With each of the percentages from the three different resource categories, the project manager can provide the proper information to his team to reduce the largest number of risks to help ensure the project finishes on time.

The Palisade @Risk software creates a probability distribution chart showing the simulation results for each of the outputs. This provides the project manager with an in-depth insight into the outcome of the project by viewing the distribution of the results such as the probability distribution chart, a tornado diagram of the output of means, and a tornado diagram of the contribution to variance. Once the risks are identified, the project manager and his team can then begin to build a plan to mitigate or avoid potential risks based on the results from the model and the experience of the individuals working on the project. One example of an output chart the Palisade @Risk software produces is a probability distribution histogram chart which provides detailed statistics for each task within the project schedule. The probability distribution histogram chart for this project is shown in Figure 4-8.

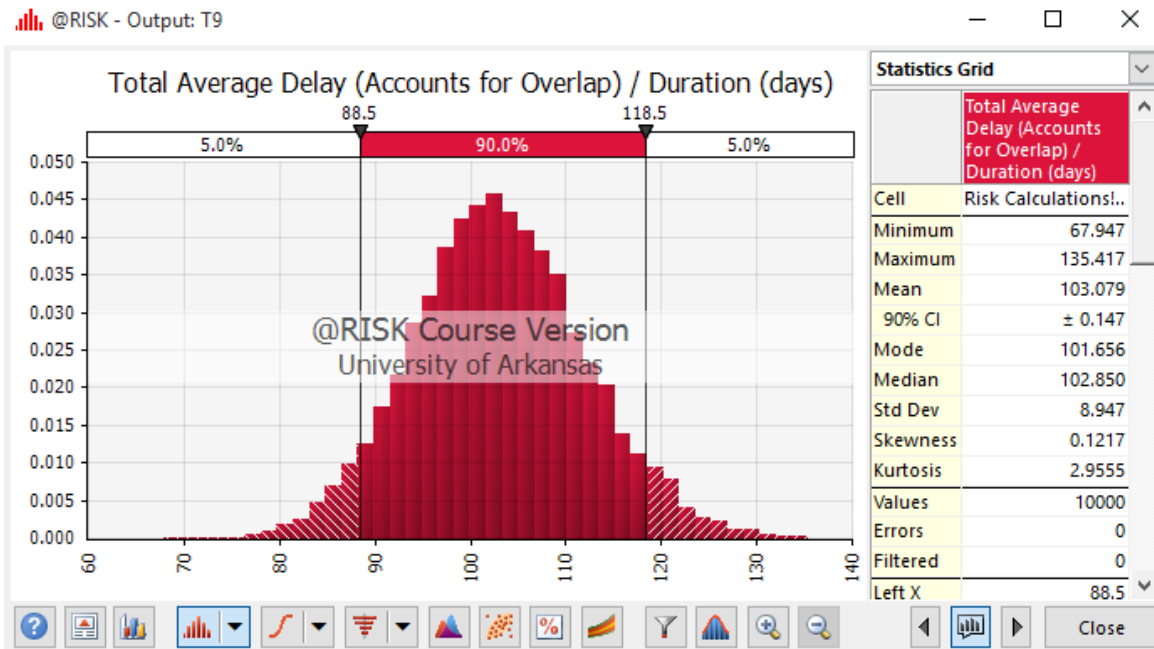


Figure 4-8: Total Average Delay - Probability Distribution

The project manager can see that the minimum number of delays from the simulation is 68 days while the maximum is 144 days. The average number of delays from all 10,000 trials is 103 days with 90% of the results ranging between 89 and 119 days. The Palisade @Risk also produces a tornado diagram showing the inputs ranked by effect on the output mean which shows the task and risk aggregate with the largest effect on the output mean for the project. The tornado diagram showing the inputs ranked by effect on the output mean for this research is shown in Figure 4-9.

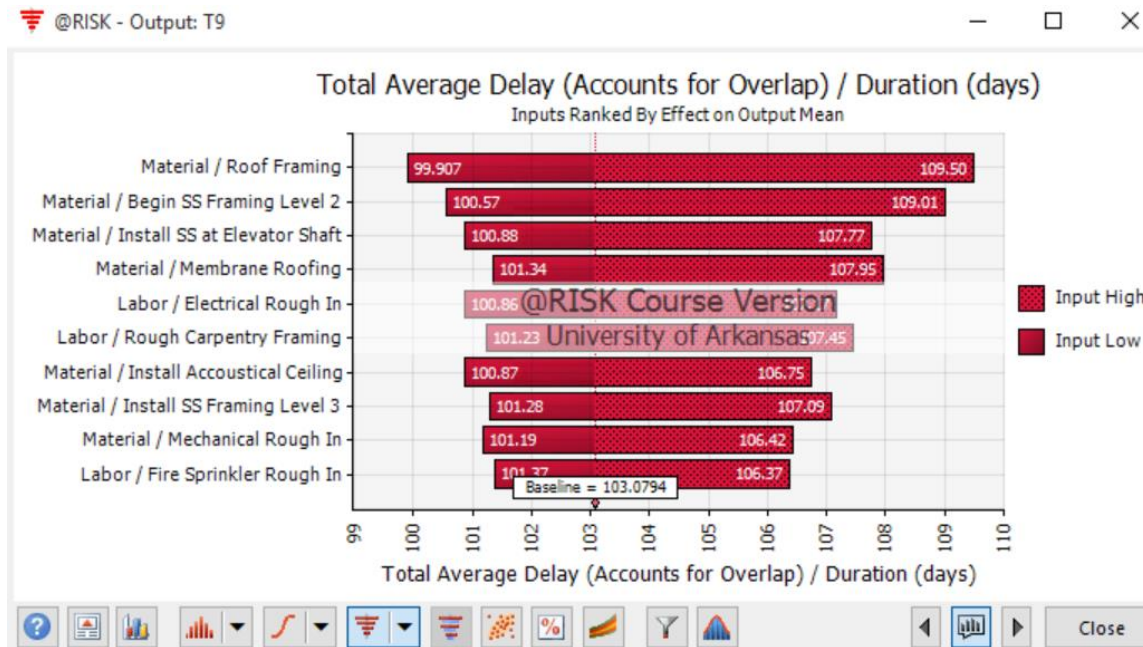


Figure 4-9: Total Delay – Tornado Diagram Output Mean

This tornado diagram shows the project manager which inputs are causing the average output of 103 days to change the most. The largest input task of “Roof Framing” and risk aggregate of “Material” have an overall effect on the output mean ranging between 100 and 110 days. Of the ten tasks and risk categories listed in the tornado diagram, seven of them include the risk category of material. This is most likely because the materials required for the project could not be acquired on the island of Hawaii and had to be shipped in from the mainland. The team and project manager should focus more time developing a risk mitigation strategy for the tasks shown on the chart because they are the ones affecting the output mean for the project. Another diagram that can be used in combination with the inputs ranked by effect on output mean tornado diagram, is the contribution to variance tornado diagram. This diagram shows which tasks and risk aggregates cause the largest percentage difference to the total number of delays. A project manager can then use the combination of the tornado diagrams and his experience on other

projects to see which tasks affect the overall outcome of the project and plan accordingly to reduce the risk the project runs past the deadline. The contribution to variance to the total delay for this project is shown in Figure 4-10.

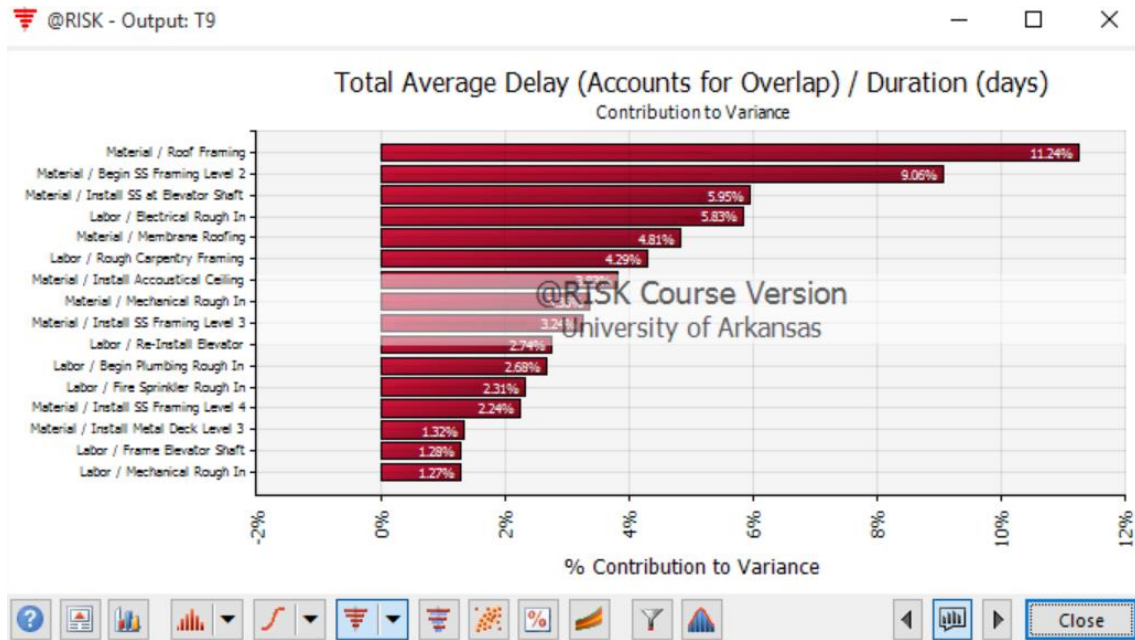


Figure 4-10: Total Delay – Tornado Diagram Contribution to Variance

The contribution to variance tornado diagram from the model results includes sixteen tasks within the project schedule with the highest percentage of variance being 11.24%, while the lowest percentage is 1.27%. Of the sixteen tasks shown to have the highest contribution to the variance of the project, nine of them are associated with the material risk category while seven are associated with the labor risk category. This insight into the project schedule allows the project manager to pinpoint the largest task and risk category for the project which accounts for more than a tenth of the variance in the schedule. After the tasks with the largest potential delays have been identified, which often is the most difficult part of creating a risk mitigation plan, the

team and project manager will be able to develop a detailed plan of action as the task becomes a potential issue.

After the analysis of the project was completed, the information was compared to the real outcome from the project and discussed with the project manager. The original project schedule was from 06/06/13 and was used as the starting point for developing the model, while the final complete project schedule was from 09/24/13. The final complete schedule differed from the original schedule with the addition of five new tasks. After talking with the project manager (SME #1), the new tasks were added to the original project schedule due to a design change that the owner requested. This caused a delay within the project schedule prior to the group of tasks labeled “Crane on-site @ Courtyard” because the original project schedule did not incorporate this design change or scope change. The new tasks, duration, and risk aggregate can be found in Table 4-11.

Table 4-11: New Tasks within Project Schedule

Task Number	Task Name	Duration	Resource Type
33	CCI directed off-site	23 days	Scope Change
34	Receive direction so Structural Steel can proceed	10 days	Scope Change
35	Detail Steel Shops	10 days	Scope Change
36	Submit Steel Shops – Receive Approval	10 days	Scope Change
37	Structural Steel Delay	65 days	Material

The first four tasks are caused by a design change caused by the owner of the building requesting additional office spaces. For this reason, the project manager could not be held responsible for these delays as they were not in the original scope of the project. The last delay titled “Structural Steel Delay” is a delay caused by a specialty structural steel that was not available on Hawaii. This required the structural steel to be ordered from the mainland and shipped to the project’s

location causing a 65-day delay to the deadline of the project. These delays can be seen in the final completed project schedule from 09/24/13 which can be found in Appendix F, although it has a poor resolution and is difficult to read.

To compare the real outcome with outcome predicted from the model, the delays from Table 4-9 were transferred into Microsoft Project to determine the affects the predicted delays had on the project schedule. This allows the project manager to calculate the critical path of the project as well as to determine the overall added time to the finish date for the project. Because not all the predicted delays occurred on tasks on the critical path, the overall duration was extended 45 days despite there being a total of 103 days of delays predicted from the Monte Carlo simulation. The section of the schedule including the group of tasks with the header of “Begin Project Demo” in the project schedule was delayed 7 days despite the 18 days predicted from the Monte Carlo simulation results, increasing the total duration from 61 to 68 days. Another major section of the project schedule affected by the delays predicted by the model was the group of tasks with the header of “Crane on-sight @ Courtyard”, which was delayed by 26 days despite the 35 days predicted by the Monte Carlo simulation results, increasing total duration from 53 to 79 days. A sample created of the project schedule in Microsoft Project with the delays added can be seen in Figure 4-11. Only the first 16 tasks are visible for illustrative purposes.

Task #	Out Nu	Task Name	Duration	Start	Finish	Predece	Critica
1	1	Project Duration	290 days	Wed 5/29/13	Tue 7/8/14		Yes
2	2	Mobilize @ Laydown	3 days	Wed 5/29/13	Fri 5/31/13		No
3	3	Mobilize @ Job Site	5 days	Thu 6/6/13	Wed 6/12/13		No
4	4	Set up perimeter scaffold and barrier	5 days	Thu 6/6/13	Wed 6/12/13	3SS	No
5	5	Elevator Dismatle by Otis	11 days	Mon 6/10/13	Mon 6/24/13	3SS+2 day	No
6	6	Electrical Disconnect and Drop	6 days	Mon 6/10/13	Mon 6/17/13	3SS+2 day	No
7	7	Set up Temp Power	1 day	Mon 6/10/13	Mon 6/10/13	6SS	No
8	8	Mechanical Disconnect and Drop	6 days	Mon 6/10/13	Mon 6/17/13	6SS	No
9	9	Begin Project Demo	68 days	Thu 6/6/13	Mon 9/9/13	3SS	No
10	10	Remove Metal Gates	1 day	Thu 6/6/13	Thu 6/6/13	3SS	Yes
11	11	Protect Pavers/Courtyard Brick	1 day	Thu 6/6/13	Thu 6/6/13	10SS	No
12	12	Remove 2nd Floor Windows @ Chute	1 day	Thu 6/6/13	Thu 6/6/13	10SS	Yes
13	13	Remove Ceiling (STO) @ Interior Courtyard	1 day	Fri 6/7/13	Fri 6/7/13	12	Yes
14	14	Install Handrail @ Roof	1 day	Fri 6/7/13	Fri 6/7/13	13SS	No
15	15	Open Trash Chute @ Roof	1 day	Fri 6/7/13	Fri 6/7/13	13SS	No
16	16	Install Temp Cover for Roof	1 day	Fri 6/7/13	Fri 6/7/13	13SS	Yes

Figure 4-11: Project Schedule with Delays in Microsoft Project (Tasks 1 – 16)

After the delays were added to the project schedule, a new critical path calculation must be conducted to determine if delays caused any changes to the project. The critical path for the project with the delays can be seen in Table 4-12.

Table 4-12: Critical Path with Delays

Task #	Name	Start	Finish
1	Project Duration	Wed 5/29/13	Tue 7/8/14
10	Remove Metal Gates	Thu 6/6/13	Thu 6/6/13
12	Remove 2 nd Floor Windows @ Chute	Thu 6/6/13	Thu 6/6/13
13	Remove Ceiling (STO) @ Interior Courtyard	Fri 6/7/13	Fri 6/7/13
16	Install Temp Cover for Roof	Fri 6/7/13	Fri 6/7/13
17	Install 5 th Floor Handrail	Mon 6/10/13	Mon 6/10/13
18	Open Trash Chute @ 5 th Floor	Mon 6/10/13	Mon 6/10/13
19	Install 4 th Floor Handrails	Tue 6/11/13	Tue 6/11/13
20	Open Trash Chute @ 4 th Floor	Tue 6/11/13	Tue 6/11/13
21	Install 3 rd Floor Handrails	Wed 6/12/13	Wed 6/12/13
22	Open Trash Chute @ 3 rd Floor	Wed 6/12/13	Wed 6/12/13
23	Soft Demo Level 5	Thu 6/13/13	Tue 6/18/13
24	Soft Demo Level 4	Fri 6/14/13	Wed 6/19/13
25	Soft Demo Level 3	Mon 6/17/13	Mon 7/1/13

Table 4-12 (Cont.)

Task #	Name	Start	Finish
26	Soft Demo Level 2	Thu 6/20/13	Thu 7/4/13
27	Shore Stairways	Fri 7/5/13	Fri 7/5/13
28	Install Protection @ Windows	Fri 7/5/13	Fri 7/5/13
29	Dismantle Roof Units and Accessories	Mon 7/8/13	Mon 7/22/13
30	Demo Roof Structure	Mon 7/15/13	Mon 7/22/13
31	Demo 5 th Structure	Tue 7/23/13	Tue 7/30/13
32	Demo 4 th Structure	Wed 7/31/13	Wed 8/7/13
33	Demo 3 rd Structure	Thu 8/8/13	Wed 8/14/13
34	Demo 2 nd Structure	Thu 8/15/13	Thu 8/22/13
35	Demo ALL 1 st Floor	Fri 8/23/13	Mon 9/9/13
37	Begin SS Framing Level 2	Tue 9/10/13	Wed 9/25/13
40	Install SS Framing Level 3	Tue 10/1/13	Mon 10/14/13
42	Install SS Framing Level 4	Fri 10/18/13	Thu 10/31/13
43	Install Metal Deck Level 4	Fri 11/1/13	Mon 11/11/13
44	Install SS Framing Level 5	Tue 11/19/13	Fri 11/29/13
45	Install Metal Deck Level 5	Mon 12/2/13	Tue 12/10/13
54	Rough Carpentry Framing	Wed 12/11/13	Mon 2/3/14
60	Mechanical Rough In	Tue 1/21/14	Fri 2/21/14
61	Hang Drywall, Tape and Mud	Mon 2/24/14	Tue 4/8/14
62	Install CT	Wed 4/9/14	Thu 5/8/14
66	Cabinets, Trims, Acc	Fri 5/9/14	Fri 5/23/14
67	Paint	Mon 5/26/14	Tue 6/17/14
68	Install Acoustical Ceiling	Wed 6/18/14	Fri 7/4/14
70	Punch	Mon 7/7/14	Mon 7/7/14
71	Turnover	Tue 7/8/14	Tue 7/8/14

The critical path for the project after the delays combined for 39 tasks with a start date of 05/29/13 and finishing on 07/08/14. The duration for the project schedule with delays is 290 days. After comparing the critical path from the original project schedule to the final complete project schedule, the tasks within the critical path remained the same. Although the tasks did not change, the project manager can quickly determine that the main difference between the two project schedules is the final turnover date, which was extended from 05/06/14 to 07/08/14; resulting in a total delay of 45 working days, or nearly 2 months. Once the project analysis was

completed and compared, a meeting was set up to discuss the outcome and validity of the results with the project manager (SME #1) who oversaw the project.

When discussing the project with the project manager (SME #1), he confirmed the results for the project appeared to be realistic for the outcome of the project. Because this project was completed nearly three years ago, he could not remember any of the specific informal risk mitigation procedures used daily for each of the tasks in the project schedule. When asked if the model results would have been useful on the project, he responded with “the brewery contractor [who worked alongside of him] could have benefitted from something like this because it could have predicted the delay that actually happened.” The brewery contractor was in charge of overseeing the project manager. The project manager mentioned in the interview that “he had little experience with this project type, so he significantly failed in meeting his schedule.” This caused the project to fall behind 65 days based on the original scope and 118 days with the new design change because he lacked the experience required to oversee the project and to ensure the project met the final deadline.

4.8. Data Analysis Conclusion

After conducting the analysis from the model developed for this research, it would be premature to draw definitive conclusions about all projects because this research was a case study of one construction project. The model needs to be tested and analyzed with projects with a similar scope, budget, and schedule and if the results continue to show promise, then projects with a larger size need to be analyzed. Because the project used for this analysis was already completed, many of the daily details of the project were lost because the project manager working the project could not remember the fine details.

A follow-up interview was conducted with each SME to discuss their opinion and viewpoint on the outcomes of the model. One of the interview questions asked was whether they would consider using the model in the future. Four of the five SMEs indicated that they would consider using the analytical model for a future project because of its ability to predict delays prior to the start of the project. A combination of the project manager's experience and the analytical model output can be a powerful tool to help ensure the projects are completed on time.

Based on the results from the data analysis conducted for this research and the follow-up interviews from the SMEs, the model shows promise and should be tested with additional projects. Because no two construction projects are the same, a definitive conclusion cannot be made because only one project was analyzed. It would be beneficial for a research team to work alongside a project manager from the start to end of the project. This would allow for better insight as to the day-to-day operation of a project to determine the informal risk mitigation plan a project manager uses to combat the potential delays.

5. Conclusions and Future Work

5.1. Summary of Research Goals and Objectives

The purpose of this research was to create an analytical model to help the project manager identify potential delays associated with the resource allocation process using Monte Carlo simulation prior to the start of a construction project. The work completed for this project is an in-depth case study of a project to test the effectiveness of the analytical model built; however, more research needs to be conducted using similar projects before a definitive conclusion can be drawn and the results can be generalized. Specifically, this research has a primary objective to develop an analytical model to determine potential delays within the resource allocation process by performing Monte Carlo simulation by:

- Conducting an in-depth literature review of the materials management and resource allocation research being conducted in the construction industry;
- Developing a model with which a project manager with little to no risk management experience can quickly and accurately assign probabilities and potential delay times;
- Interviewing subject matter experts (SMEs) to gather insight into the construction industry and potential usefulness of the model;
- Defining each of the three major resource categories used for each task namely equipment, materials, and labor;
- Verifying the model is working properly by replicating the results from a previous project;
- Performing an in-depth case study to demonstrate the effectiveness of the model by comparing the results to a previously completed project to perform validation of the model; and
- Identifying areas for future work so the research can be expanded.

An in-depth case study was conducted to show the potential effectiveness of a model used to predict uncertainties every construction project experiences; allowing the project manager to better predict certain delays so cautionary steps can be taken to reduce the negative effects of delays on the overall deadline of the project.

5.2. Outcomes from Literature Review

The literature review surveyed the general body of knowledge relating to resource allocation, scheduling methods, and portfolio management within the construction industry. The study found that research in the construction industry is lacking in the following areas:

- effects of a project managed with a scheduling software such as Microsoft Project or Oracle Primavera;
- analytical modeling tools or software the project manager can use;
- delays caused by the resource allocation process; and
- risk management using Monte Carlo simulation.

Some research is being conducted on the general delays of a project, but no studies have been found investigating the effects the resource allocation process has on the delays within a schedule. Research being conducted by investigators from the Construction Industry Institute (CII) focuses on the materials management and scheduling process with few studies looking to understand the specific reasons behind the occurrence of a delay. This supports the development of an analytical model used to anticipate the potential delays caused by resource allocation by using the Monte Carlo simulation approach.

5.3. Observations from the Data Collections

During the data collection process, there were several instances in which the project manager was reluctant to provide the project data required for the analysis to be conducted. Despite asking for projects that have already been completed, several project managers and/or companies were unwilling to give up specifics related to a project for fear of giving up company secrets and procedures unique to each business. Because a general contracting firm produces a profit based on the accuracy of the initial project bid and the effectiveness of a project manager in sticking to the timeline and cost of the bid, these individuals being unwilling to provide insights into how the company operates provided a unique challenge to collecting data.

Despite the difficulties to provide product data, several project managers were willing to conduct an interview to help develop and build a model to predict the potential delays within the

resource allocation process. One reason for the unwillingness to provide data for the project by one of the project managers contacted was the amount of time required to provide a full set of project data, where an interview could be conducted in two thirty-minute sessions. The first interview was used to gather the demographic information for each of the subject matter experts (SMEs) as well as some basic project information to help develop a model. After the analysis was conducted, a follow-up interview was conducted to determine the usefulness of the model and if they would implement a similar model within their own company.

5.4. Outcomes of the Data Analysis

The data analysis consisted of comparing the original project schedule to the delays predicted by the model to determine the potential outcome for the project. The following are a list of the key results from the data analysis:

- One renovation project was used for the analysis from a project manager located on the island of Hawaii.
- An interview was conducted of five subject matter experts (SMEs) to gather insight to develop the model and to gather their viewpoints of the usefulness of the model.
- The original project schedule from 06/06/13 started on 05/29/13 with an end date of 05/06/14 for a duration of 245 days.
- The original project schedule task header named “Begin Project Demo” tasks combine for a total duration of 61 days.
- The original project schedule task header named “Crane on-site @ Courtyard” tasks combine for a duration of 53 days.
- The delays predicted from the model resulted in a total average of 103 days.

- The delays accounted for an additional duration of 45 days because not all 103 of the delay days affected the tasks on the critical path.
- The final complete schedule from 09/24/13 accounted for 118 days of delays with 65 days of material delay from the original project scope.
- The final complete schedule from 09/24/13 and finished on 12/02/14 for a duration of 395 days.
- The critical path of the project did not change despite the predicated delays being added to the project schedule.

After the analysis of the research was completed, a follow-up interview was conducted with the project manager of the project to validate the results of the project. One issue discovered during the interview was that the informal day-to-day operation procedures were lost because of the amount of time that elapsed from the completion of the project to the follow-up interview.

5.5. Conclusions

This research effort demonstrates the results from an in-depth case study of a project to determine if the model showed promise to accurately predict delays within a project schedule prior to the start of the project. Because construction projects face risks of delays daily, it is nearly impossible to predict every possible delay associated with each task. For this reason, it is recommended the model be used with projects with a similar scope, cost, and timeline to the project analyzed. If the results continue to show promise in detecting potential delays, the size and scope of the project should continue to increase. Another important component of the model was it was retrospective with the project already being finished. If a research team could work alongside a project manager throughout the project, the analysis would provide greater insight since many of the informal risk mitigation procedures are not recorded and lost with time.

5.6. Future Work

There are three main areas of future work that could provide benefit to the construction industry. The first major area not considered in this model was the component of cost. When a task is put on the fast track, oftentimes a major consideration is cost or the financial portion of a project. A project manager must consider if the increase of time it takes to complete a task is worth the added cost. Ultimately, a general contracting firm must turn a profit on each of the projects or risk going bankrupt because they no longer have the funds required to conduct business.

The second main area of future work a research team must consider in the development of a model is to use a software package all project managers have access to download. Although the research was conducted using the Palisade @Risk software, other Monte Carlo simulation software including Probability Management's SIPmath or Oracle's Crystal Ball. The SIPmath software lacks in the detailed visual reports and charts created using the @Risk software; however, because the software is free to download, there is a greater likelihood a general contractor will test it out because there are no additional financial requirements. One advantage to using SIPmath is it can be downloaded online free of charge where other Monte Carlo simulation software can cost thousands of dollars. If a project is already scheduled using the Oracle Primavera software, the Oracle Crystal Ball software can be applied to the project with relative ease.

The last main area of future work is to apply the model in other industries. Because the risk categories can be added or removed based on the needs of the industry, the potential uses are endless. The project manager can also change resource category names depending on the needs of project. The uses for an analytical model, similar to the one developed in this research, are adaptable and scalable for all project managers working in any industry.

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Appendix A: Implied Consent Agreement Form

10/18/2017

To Who It May Concern:

My name is Colby Weishaar and I currently am a graduate student at the University of Arkansas pursuing my MS in Industrial Engineering. My research focus is on the effects of improper risk management on the resource allocation process seeing if we can predict potential hazards before they occur using Monte-Carlo Simulation within the construction industry. One of my main interests within engineering is to improve the project management process by implementing new technology or techniques to assist project managers in completing projects on schedule and within budget.

You are invited to participate in a structured interview where you will answer a few questions in the attached file regarding the study. You were selected as a possible participant in this study because of your expertise and your responsibility for various project data and project management important to my study.

If you decide to participate in this voluntary study and interview, we will proceed with discussing the attached set of questions. By agreeing to be interviewed, you have implied your consent to participate in this study. Record of this interview will be kept in the form of handwritten or typed notes for the duration of this study. Audio and video recording of the interview will not be used. At any point you can choose to not answer a question or withdraw from participating in this interview. No benefits accrue to you for answering the questions in this interview, but your responses will be used to help understand the impact of the study within the construction industry.

Any information that is obtained in connection with this interview and that can be identified with you will remain confidential and will not be disclosed. Any identifiable information will be kept confidential to the extent allowed by law and University policy.

If you have any questions, concerns, or complaints about this study or interview, you may contact the primary researcher at this address:

Colby Weishaar
Department of Industrial Engineering
4207 Bell Engineering Center
University of Arkansas
Fayetteville, AR 72701
913/530-3270
ctweisha@uark.edu

You may also contact the thesis advisor overseeing the study at this address:

Dr. Kim LaScola Needy, Dean
Graduate School and International Education
213 Gearhart Hall
University of Arkansas
Fayetteville, AR 72701
479/575-4401
kneedy@uark.edu

If you have any questions regarding your rights as a research subject, please contact:

Irosh Windwalker
IRB Coordinator
Office of Research Compliance
109 MLKG
1424 W. Martin Luther King, Jr.
Fayetteville, AR 72701
479/575-2208
iwindwal@uark.edu

We appreciate your willingness to participate. Thank you for your time.

Sincerely,

Colby Weishaar

Appendix B: Complete List of Interview Questions

Demographic Information:

1. How many years have you worked in the construction industry?
2. How many years have you worked for your current company?
3. What is your current job title?
4. What industry are the types of projects you are working on, e.g., health care, warehouse, manufacturing, office buildings, residential, or other?
5. What is the size of the project you are currently working on with respect to total cost, number of personnel, total labor hours, and project length?

Project Information:

1. How is risk management resource allocation currently handled in your company?
2. What are the primary types of risk that you manage, i.e., natural disasters, resources shortages, personnel?
3. How comfortable are you identifying and assigning risk probabilities?
4. How would you suggest breaking up the risks used for analysis i.e. using an aggregates/categories or determining the most important/crucial risks for a task?
5. If you use aggregates/categories, what categories would you use i.e. equipment, materials, labor, etc?
6. How do you think the construction industry is moving to adopt new software or tools to support?
7. Would the industry be willing to adopt tools used in this study?
8. Should this study be analyzed with additional projects?
9. Are you satisfied with your current technique?
10. How useful was this study in applying it to your current company?
11. Are there any pitfalls to a software or tool similar to the one used in the study?
12. Do you have any suggestions in improving the study?
13. Would you consider using this tool on future projects?

Appendix C: IRB Paperwork

Figure C-1: IRB Protocol Number Paperwork



To: Colby Taylor Weishaar
BELL 4188

From: Douglas James Adams, Chair
IRB Committee

Date: 10/19/2017

Action: **Exemption Granted**

Action Date: 10/19/2017

Protocol #: 1710078236

Study Title: Resource Allocation Scheduling Risk Management using Monte Carlo Simulation

The above-referenced protocol has been determined to be exempt after review by the IRB Committee that oversees research with human subjects.

If the research involves collaboration with another institution then the research cannot commence until the Committee receives written notification of approval or exemption from the collaborating institution's IRB.

Adverse Events: Any serious or unexpected adverse event must be reported to the IRB Committee within 48 hours. All other adverse events should be reported within 10 working days.

Amendments: Any changes to the protocol that impact human subjects, including changes in experimental design, equipment, personnel or funding, must be approved by the IRB Committee before they can be initiated.

You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with the IRB Committee, original signed consent forms, and study data.

cc: Kim LaScola Needy, Investigator

Appendix D: Verification Model and this Analytical Model Results

Table D-1: Simulation Results of Each Activity from Wang and Huang Model

Simulation Results of Each Activity from Previous Model								
Activity (i, j)	Estimated Delay (days)			μ (i,j)	σ^2 (i,j)	σ (i,j)	Min	Max
	<i>a</i>	<i>m</i>	<i>b</i>					
A (1, 2)	30	36	42	36.06	3.99	2.00	30.74	41.67
B (1, 3)	36	40	44	40.04	1.77	1.33	36.50	43.78
C (1, 4)	30	40	50	40.1	11.08	3.33	31.24	49.45
D (2, 5)	30	40	50	40.1	11.08	3.33	31.24	49.45
E (2, 6)	7	10	13	10.03	1.00	1.00	7.37	12.84
F (3, 6)	38	40	42	40.02	0.44	0.67	38.25	41.89
G (4, 6)	8	10	12	10.02	0.44	0.67	8.25	11.89
H (4, 7)	20	32	44	32.13	15.95	3.99	21.49	43.34
I (5, 8)	14	20	26	20.06	3.99	2.00	14.74	25.67
J (6, 8)	18	20	22	20.02	0.44	0.67	18.25	21.89
K (7, 8)	10	20	30	20.1	11.08	3.33	11.24	29.45

where

a = optimistic time estimate

b = pessimistic time estimate

m = most likely time estimate

μ = average delay

σ^2 = variance of delay

σ = standard deviation of delay

Min = minimum delay

Max = maximum delay

Table D-2: Simulation Results of Each Activity from this Analytical Model

Simulation Results of Each Activity from this Research Model								
	Estimated Delay (days)							
Activity (i, j)	Worst	Base	Best	u_{ij}	σ^2_{ij}	σ_{ij}	Min	Max
A (1, 2)	-6	0	6	6.47E-06	6.00	2.45	-5.93	5.97
B (1, 3)	-4	0	4	2.62E-06	2.67	1.63	-3.95	3.95
C (1, 4)	-10	0	10	-6.92E-06	16.67	4.08	-9.93	9.87
D (2, 5)	-10	0	10	1.78E-05	16.67	4.08	-9.90	9.98
E (2, 6)	-3	0	3	-2.46E-06	1.50	1.22	-2.96	2.97
F (3, 6)	-2	0	2	-9.18E-07	0.67	0.82	-1.98	1.97
G (4, 6)	-2	0	2	1.98E-08	0.67	0.82	-1.99	1.97
H (4, 7)	-12	0	12	-5.83E-07	24.00	4.90	-11.90	11.93
I (5, 8)	-6	0	6	-2.65E-06	6.00	2.45	-5.94	5.95
J (6, 8)	-2	0	2	-9.43E-07	0.67	0.82	-2.00	1.97
K (7, 8)	-10	0	10	-3.04E-06	16.67	4.08	-9.89	9.94

where

a = optimistic time estimate

b = pessimistic time estimate

m = most likely time estimate

μ = average delay

σ^2 = variance of delay

σ = standard deviation of delay

Min = minimum delay

Max = maximum delay

Appendix E: Original Project Schedule – 06/06/13

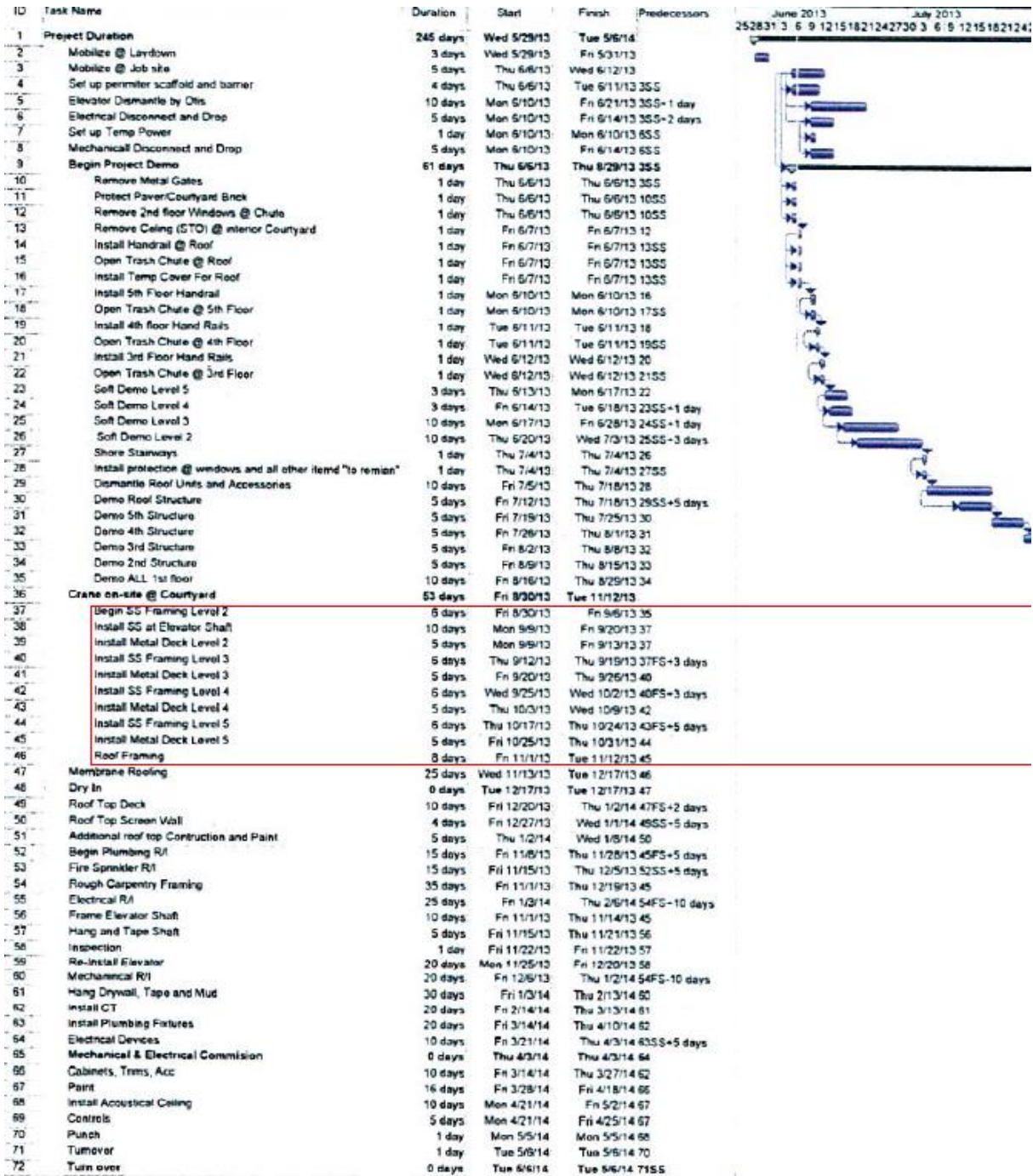


Figure E-1: Original Project Schedule – 06/06/13

Appendix F: Final Complete Project Schedule – 09/24/13

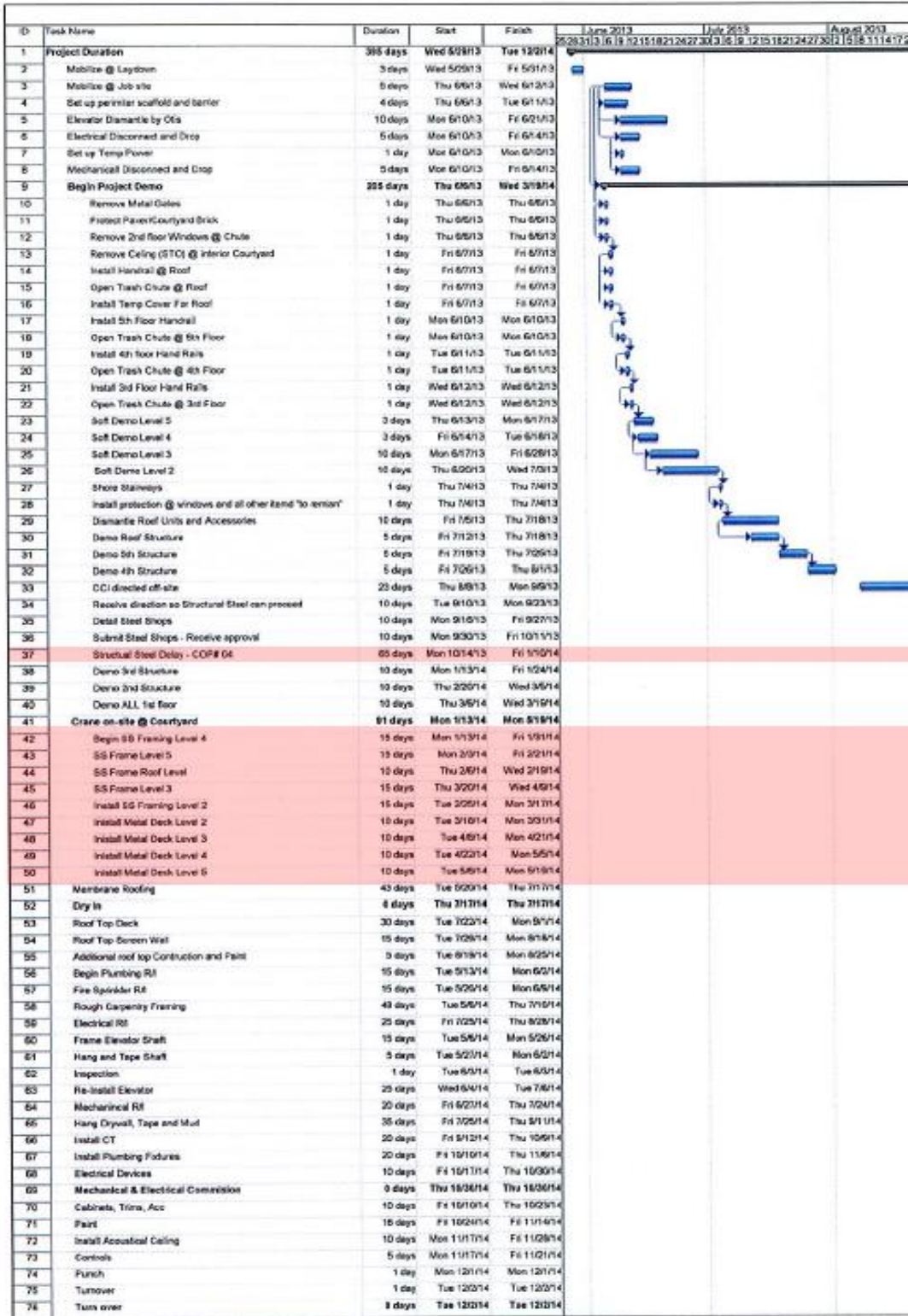


Figure F-1: Final Project Schedule – 09/24/13

Appendix G: Probability Distribution Output Charts

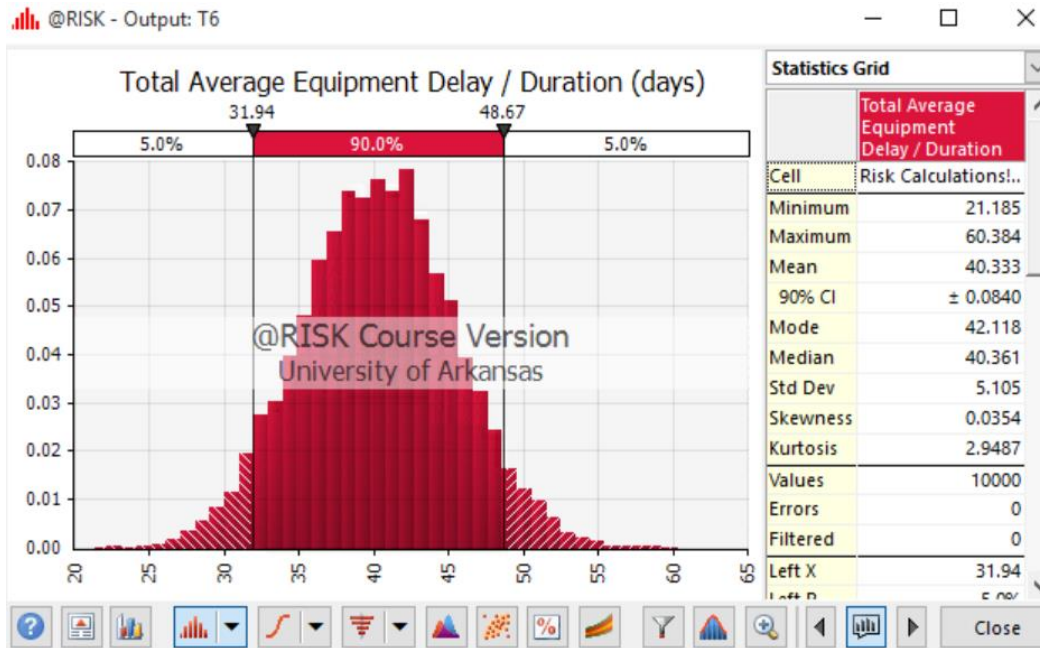


Figure G-1: Total Equipment Delay

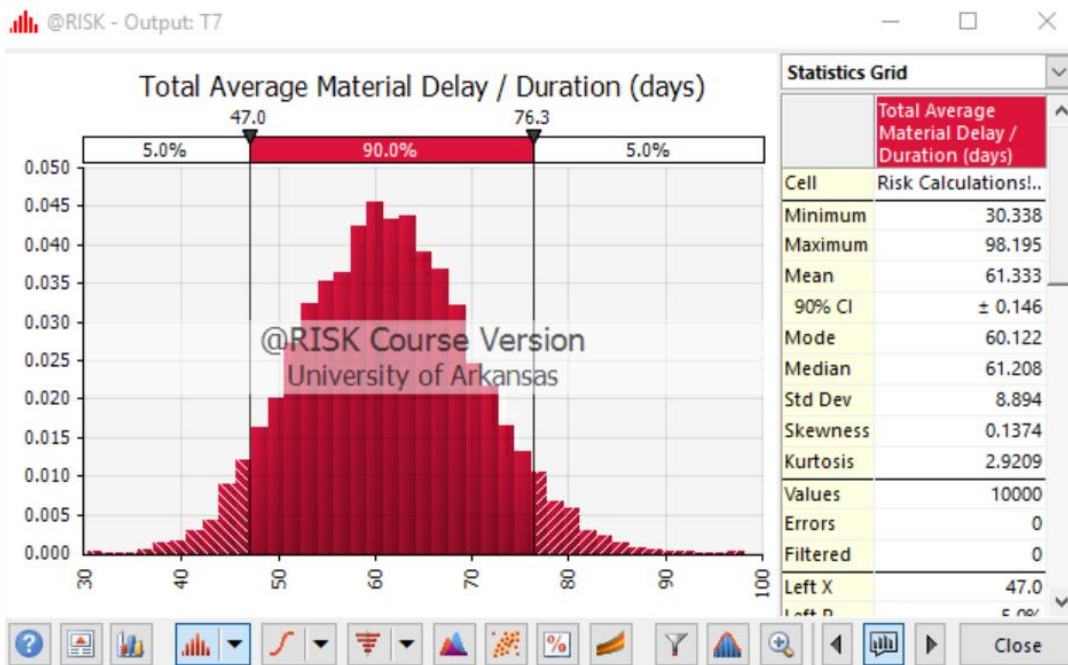


Figure G-2: Total Material Delay

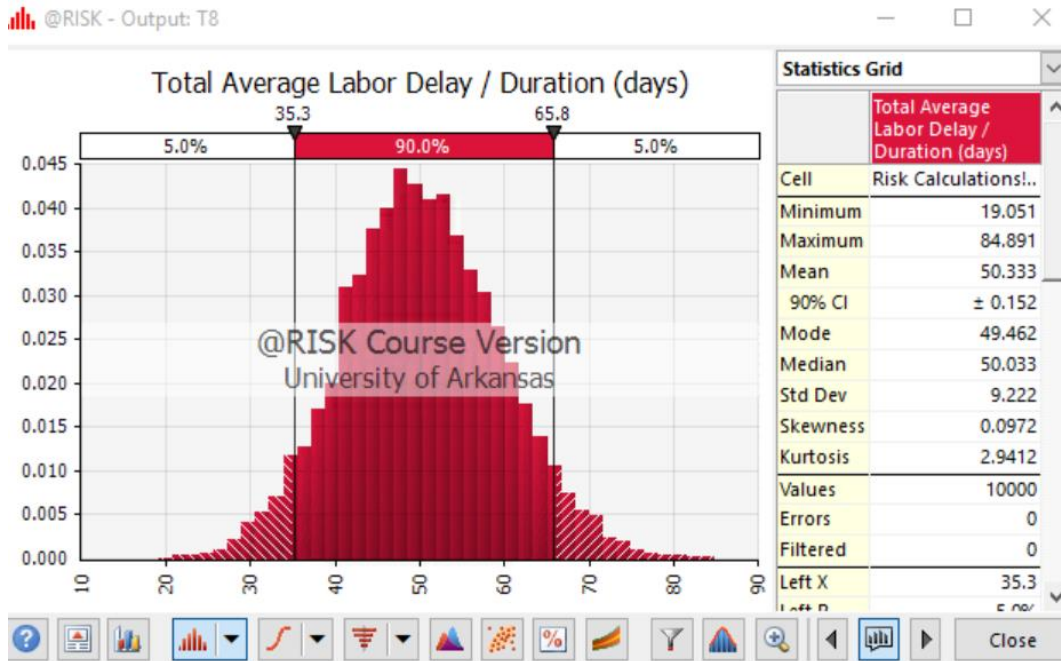


Figure G-3: Total Labor Delay

Appendix H: Tornado Diagram of Effect on Output Mean

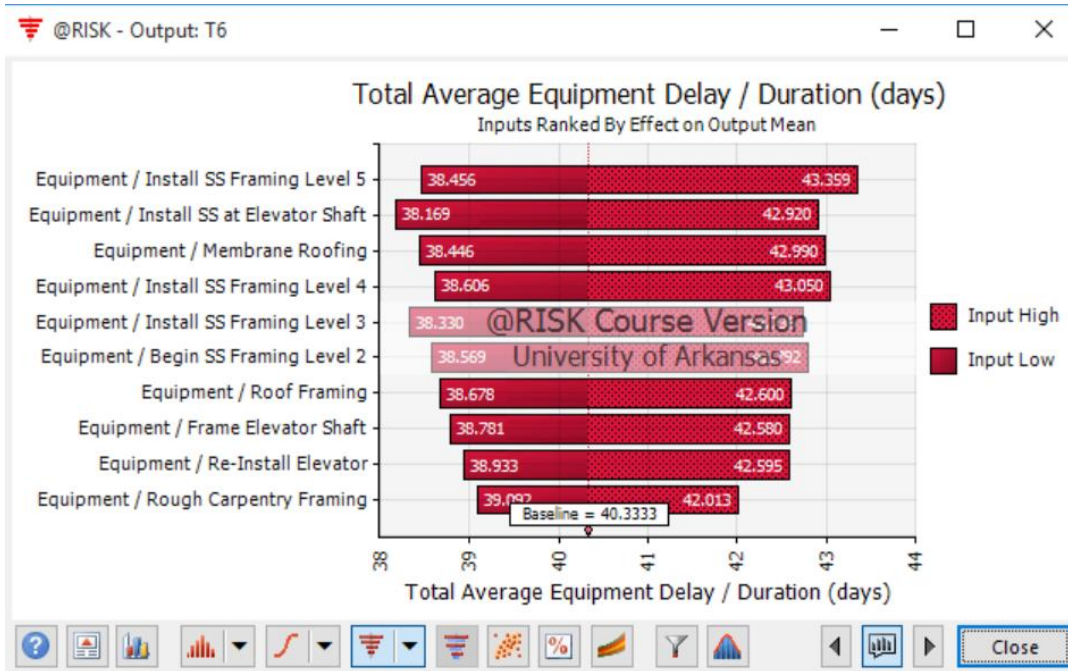


Figure H-1: Total Equipment Delay

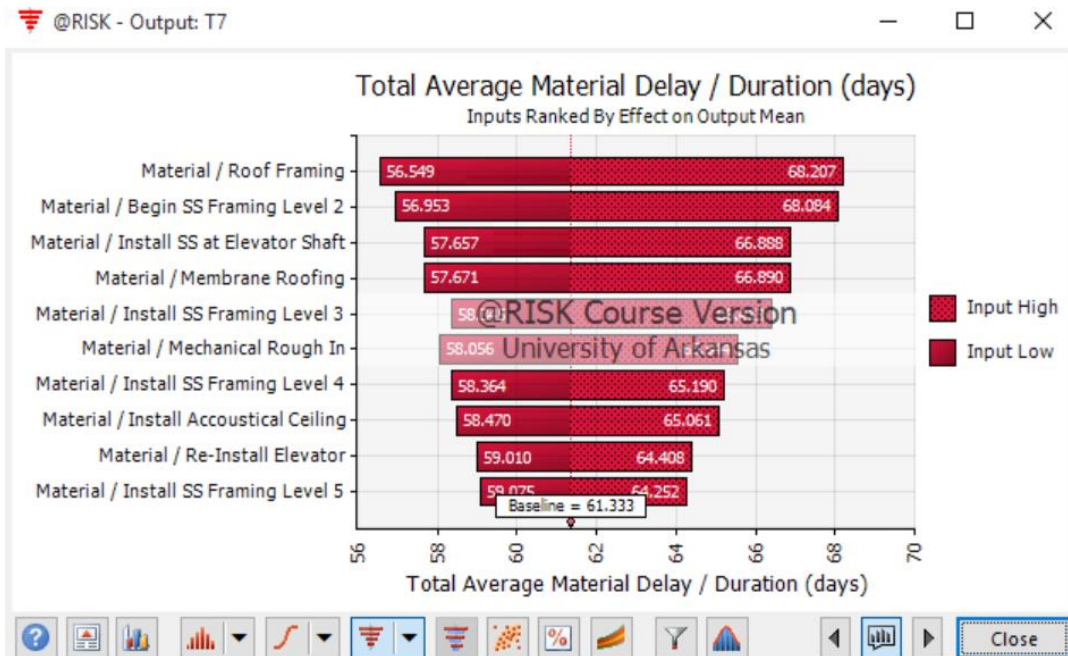


Figure H-2: Total Material Delay

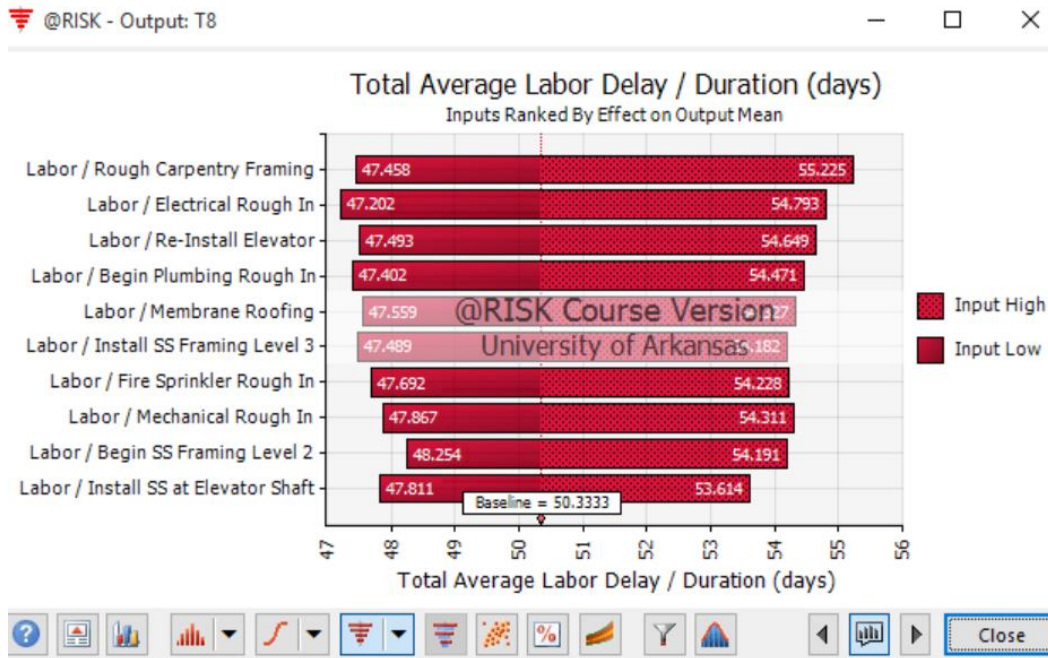


Figure H-3: Total Labor Delay

Appendix I: Tornado Diagram of Contribution to Variance

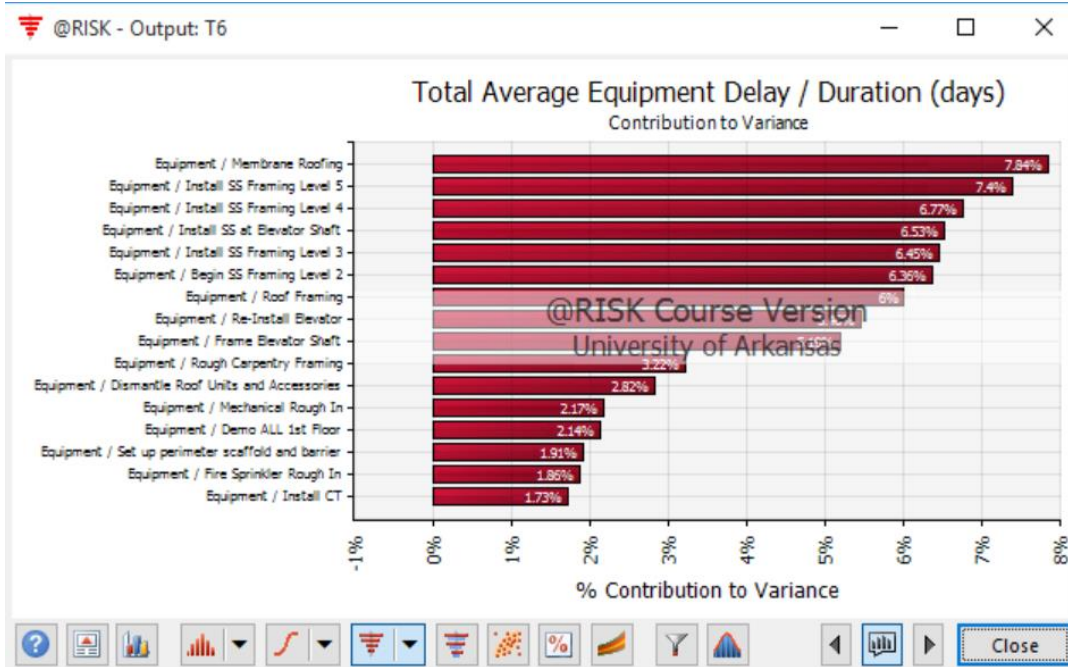


Figure I-1: Total Equipment Delay

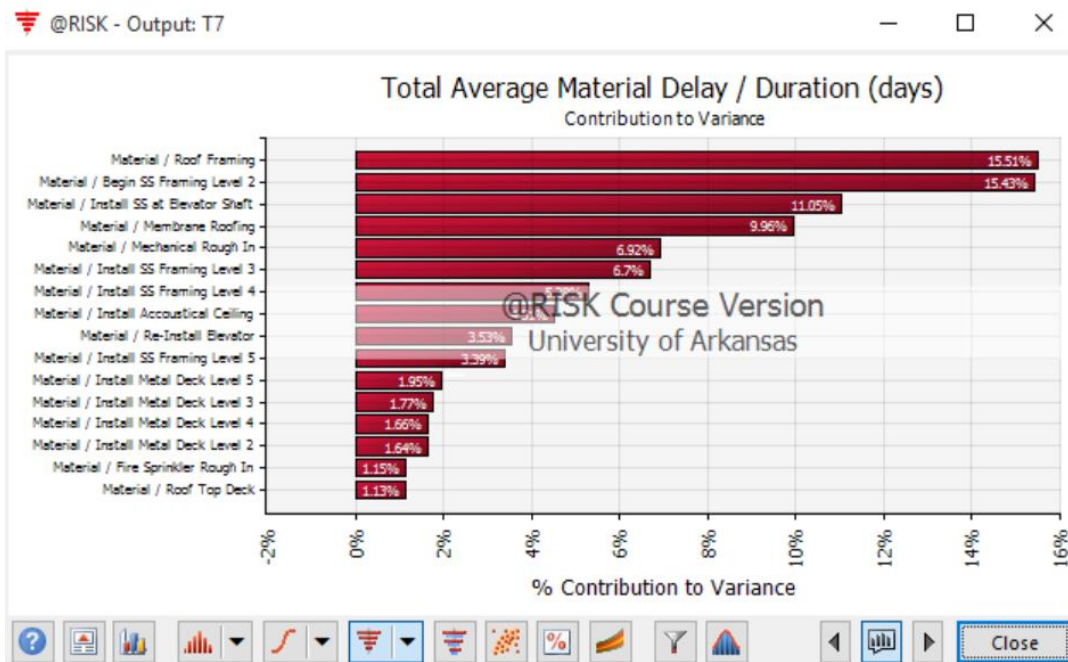


Figure I-2: Total Material Delay

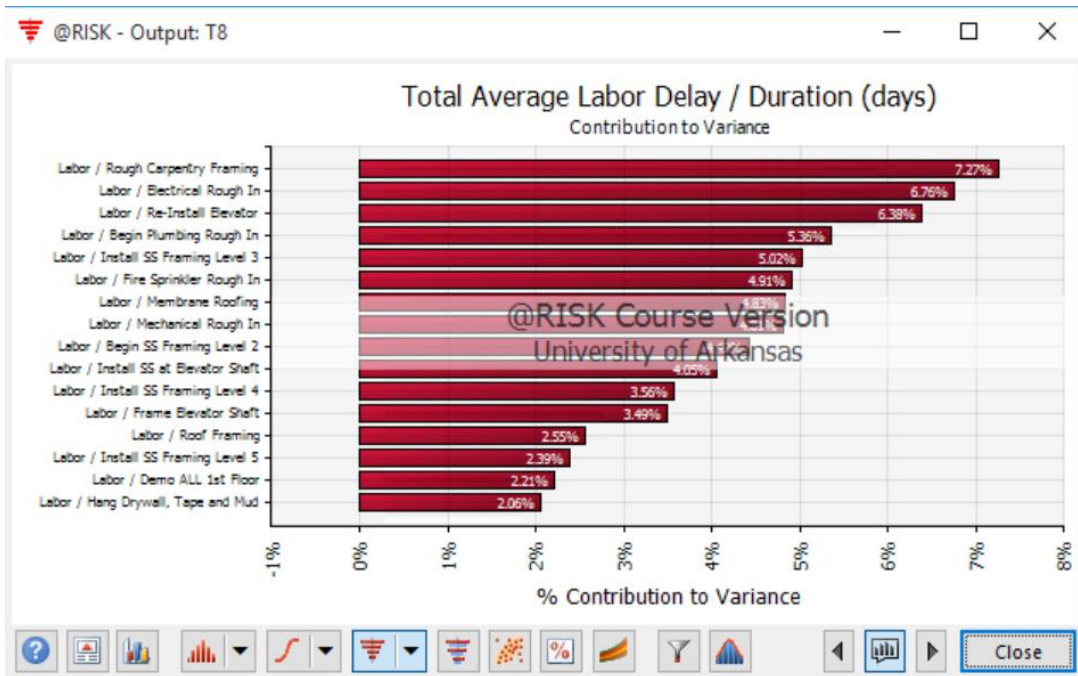


Figure I-3: Total Labor Delay

Appendix J: Detailed Statistical Analysis Report per Task

Table J-1: Detailed Statistical Analysis Report per Task

Task #	Name	Min	Max	Mean	5% Perc	95% Perc
1	Total / Project Duration	-	-	-	-	-
2	Total / Mobilize @ Laydown	-	-	-	-	-
3	Total / Mobilize @ Jobsite	-	-	-	-	-
4	Total / Set up perimeter scaffold and barrier	0	3	1	0	2
5	Total / Elevator Dismantle	0	3	1	0	2
6	Total / Electrical Disconnect	0	2	1	0	2
7	Total / Set up Temp Power	0	1	0	0	1
8	Total / Mechanical Disconnect and Drop	0	3	1	0	2
9	Total / Begin Project Demo	0	1	0	0	1
10	Total / Remove Metal Gates	0	1	0	0	1
11	Total / Protect Pavers/Courtyard Brick	0	1	0	0	1
12	Total / Remove 2nd Floor Windows @ Chute	0	3	1	0	2
13	Total / Remove Ceiling (STO) @ Interior Courtyard	0	1	0	0	1
14	Total / Install Handrail @ Roof	0	1	0	0	1
15	Total / Open Trash Chute @ Roof	0	1	0	0	1
16	Total / Install Temp Cover for Roof	0	1	0	0	1
17	Total / Install 5th Floor Handrail	0	1	0	0	1
18	Total / Open Trash Chute @ 5th Floor	0	1	0	0	1
19	Total / Install 4th Floor Handrails	0	1	0	0	1
20	Total / Open Trash Chute @ 4th Floor	0	1	0	0	1
21	Total / Install 3rd Floor Handrails	0	1	0	0	1
22	Total / Open Trash Chute @ 3rd Floor	0	1	0	0	1
23	Total / Soft Demo Level 5	0	2	1	0	2

Table J-1 (Cont.)

Task #	Name	Min	Max	Mean	5% Perc	95% Perc
24	Total / Soft Demo Level 4	0	2	1	0	2
25	Total / Soft Demo Level 3	0	4	1	0	3
26	Total / Soft Demo Level 2	0	4	1	0	3
27	Total / Shore Stairways	0	1	0	0	1
28	Total / Install Protection @ Windows	0	1	0	0	1
29	Total / Dismantle Roof Units and Accessories	0	4	1	0	3
30	Total / Demo Roof Structure	0	3	1	0	2
31	Total / Demo 5th Structure	0	3	1	0	2
32	Total / Demo 4th Structure	0	3	1	0	2
33	Total / Demo 3rd Structure	0	3	1	0	2
34	Total / Demo 2nd Structure	0	3	1	0	2
35	Total / Demo ALL 1st Floor	0	5	2	0	4
36	Total / Crane On-Site @ Courtyard	-	-	-	-	-
37	Total / Begin SS Framing Level 2	0	15	6	2	12
38	Total / Install SS at Elevator Shaft	0	12	5	1	9
39	Total / Install Metal Deck Level 2	0	5	2	0	4
40	Total / Install SS Framing Level 3	0	10	4	1	8
41	Total / Install Metal Deck Level 3	0	5	2	0	4
42	Total / Install SS Framing Level 4	0	9	4	1	7
43	Total / Install Metal Deck Level 4	0	5	2	0	4
44	Total / Install SS Framing Level 5	0	7	3	1	6
45	Total / Install Metal Deck Level 5	0	5	2	0	4
46	Total / Roof Framing	0	15	5	1	12
47	Total / Membrane Roofing	0	12	5	2	9
48	Total / Dry In	0	0	0	0	0
49	Total / Roof Top Deck	0	4	2	1	3
50	Total / Roof Top Screen Wall	0	2	1	0	2

Table J-1 (Cont.)

Task #	Name	Min	Max	Mean	5% Perc	95% Perc
51	Total / Additional Roof Top Construction and Paint	0	2	1	0	2
52	Total / Begin Plumbing Rough In	0	8	3	1	6
53	Total / Fire Sprinkler Rough In	0	8	3	1	6
54	Total / Rough Carpentry Framing	0	10	4	1	8
55	Total / Electrical Rough In	0	10	3	1	8
56	Total / Frame Elevator Shaft	0	7	3	1	5
57	Total / Hang and Tape Shaft	0	2	1	0	2
58	Total / Inspection	0	1	0	0	1
59	Total / Re-Install Elevator	0	10	4	1	8
60	Total / Mechanical Rough In	0	10	4	1	8
61	Total / Hang Drywall, Tape and Mud	0	5	2	0	4
62	Total / Install CT	0	4	2	1	3
63	Total / Install Plumbing Fixtures	0	4	2	1	3
64	Total / Electrical Devices	0	2	1	0	1
65	Total / Mechanical and Electrical Commission	0	1	0	0	1
66	Total / Cabinets, Trims, Acc	0	3	1	0	2
67	Total / Paint	0	2	1	0	2
68	Total / Install Acoustical Ceiling	0	8	3	1	6
69	Total / Controls	0	3	1	0	2
70	Total / Punch	0	1	0	0	1
71	Total / Turnover	-	-	-	-	-

where

Task # = Task Number

Name = Task Name

Min = Minimum Delay

Max = Maximum Delay

Mean = Average Delay

5% Perc = 5% Percentile

95% Perc = 95% Percentile

Table J-2: Detailed Statistical Analysis Report for Total Risk Aggregate Outputs

Name	Min	Max	Mean	5% Perc	95% Perc
Total Average Equipment Delay (days) / Total Output by Resource	21	60	40	32	49
Total Average Material Delay (days) / Total Output by Resource	30	98	61	47	76
Total Average Labor Delay (days) / Total Output by Resource	19	85	50	35	66
Total Average Delay (days) / Total Output by Resource	68	135	103	89	118

Name = Total Resource Delay Category Name

Min = Minimum Delay

Max = Maximum Delay

Mean = Average Delay

5% Perc = 5% Percentile

95% Perc = 95% Percentile