Impact Assessment of Construction Supply Chain Risk Changes on Project Time and Cost

by

Hani Ahmed

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Civil Engineering

Waterloo, Ontario, Canada, 2017

Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner	**NAME:**	Mani Golparvar-Fard
	TITLE:	Professor at the University of Illinois, Civil and Environmental Engineering Department
Supervisor(s)	**NAME:**	Carl T. Haas
	TITLE:	Professor at the University of Waterloo, Civil and Environmental Engineering Department
	NAME:	Tarek Hegazy
	TITLE:	Professor at the University of Waterloo, Civil and Environmental Engineering Department
Internal Member	**NAME:**	Giovanni Cascante
	TITLE:	Professor at the University of Waterloo, Civil and Environmental Engineering Department
	NAME:	Chris Bachmann
	TITLE:	Professor at the University of Waterloo, Civil and Environmental Engineering Department
Internal-external Member	**NAME:**	Otman Basir
	TITLE:	Professor at the University of Waterloo, Electrical and Computer Engineering Department

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

The supply chain (SC) plays a key role in the construction industry. The importance of the Construction Supply Chain (CSC) is not less than that of the onsite construction phases. There are many risk factors that influence the progress of a supply chain, and it is problematic when the probabilities and impacts of these risk factors are not well defined. While many approaches have been tried in studying SCs in construction, including risk effects, no study has addressed the dynamic updating of the probability of risk events throughout the construction life cycle to effectively study the impact on project time and cost. In order to reduce the impact of unseen risk factors that may affect the progress of any construction project, it is important to have tools to predict the influence of major risk factors in advance. However, risk factors keep changing in their probabilities and impacts along a project's duration, and these changes will be more severe and have more influence if recognized later rather than earlier, and will be harder and more costly to manage. This research is aimed at helping to recognize the occurrence probabilities of risk factors during the early stages of a project and during the project execution, and aims to build a simulation model that can automatically detect risk factors in a construction supply chain, track their changes, and quantify their impact on project time and cost.

The study starts by identifying typical risk issues related to a CSC that will influence its state. Then, a model for quantifying the amount of risk by defining the probabilities and impacts for each supply chain life cycle is proposed. The main focus of this research is to build models that automatically detect and adjust changes in probabilities for the most severe risk factors associated with CSCs and then estimate their impact on cost and schedule. Four major steps will be completed in the proposed research. First, a real-world industrial construction project is identified. Second, a detailed study on the risk factors associated with the supply chain of the given project is performed. Then, these risk factors are quantified according to the automated detection models for probability change and for studying the impact of each change. Finally, using a Monte Carlo Simulation tool (@Risk), the study will examine the impact of these risk factors on an industrial project to offer a methodology for generating automated reports for project managers in order to supply them with information on the impacts on the costs and schedules for their projects. The model offer stakeholders involved in a project with a better understanding of the changes in risk so that throughout the project execution phase, they can take corrective actions and offset the negative impact of risk on project time and cost. This system can be used for supply chain planning and operation. The power of the system is its ability to respond to various what-if scenarios. The newly introduced model is validated using a real-world industrial project, and the details of the project are documented.

Acknowledgments

All praise is due to Allah almighty, who is the source of all knowledge in this world and whose countless bounties have enabled me to complete this thesis successfully. As well, I would not have been able to finish my dissertation without the guidance of my committee members, help from friends, and support from my wife, Sara Elgabry, my family, and my kids for always standing by me through both the good times and the bad.

I would like to express my deepest gratitude to my advisors, Professor Carl Haas and Professor Tarek Hegazy, for their guidance, care, and patience and for providing me with such a wonderful atmosphere for conducting my research. In addition to my advisors, I also wish to thank the rest of my thesis committee for their encouragement and insightful comments.

Special thanks also to all colleagues and graduate friends, especially the Distribution Engineering group, for sharing literature, support, and fruitful discussion.

I also offer my gratitude to my father and mother. My research would not have been possible without their help, their constant support and encouragement, and their never-failing good wishes.

Finally, I would like to acknowledge the funding support received from King Abdul Aziz University, Jeddah, Saudi Arabia.

Dedication

In loving memory of my mother, Dr. Awatif Jameel Khageer, and to my father, Dr. Magdy Abdulhamid Eissa. You were always supportive any time I needed it, and I successfully accomplished this journey thanks most of all to you.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Background

Construction is a large and fast-growing sector accounting for approximately 5% of non-farm payroll employment and 12% of self-employment in the United States (Simonson, 2005). According to the 2008 Gross Domestic Product (GDP) statistics for industry released by the United States Bureau of Economic Analysis, the construction industry did account for the slowing down of American economic growth in 2007. The construction industry also had an output of $860.6 billion in 2008, which accounted for 4.4% of the entire U.S. economic output (Bureau of Labor Statistics 2010). It accounted for 8,552,000 jobs or 4.8% of all workers in the economy (Bureau of Labor Statistics 2010). Therefore, the construction industry is a very significant component of the United States economy.

While construction in the U.S. is a large component of the economy, it also still faces several significant challenges that affect the industry. Construction projects generally involve a large number of separate firms, as projects can involve owners, designers, contractors, and sub-contractors that are all responsible for their individual elements of the project. This is a challenge for communication and accountability among participants involves a large number of small firms without resources (Manley 2014).

In the construction industry, particularly with large industrial projects, uncertainty and risk can lead to cost increases and scheduling delays, and may ultimately result in a project that is not of the scope or quality that the public and other stakeholders need. This is evidenced by the high number of projects that do not meet their cost performance goals, and one study on 258 projects over 70 years found that early project cost estimates are underestimated nearly 90 percent of the time (Flyvbjerg et al., 2012). In the same study, it was found that costs increased by an average of 28% from the point at which the decision to build was made to the completion of the project. Poor risk estimation is known to lead to such outcomes.

Poor supply chain management may account for some delays and cost overruns related to the construction industry. Generally, Construction Supply Chain Management (CSCM) involves the coordination of activities within a construction firm and between members of the supply chain (Croxton et al., 2001). A supply chain is defined as “A system of people, technology, activities, information, and resources that must exist in order to have a product delivered from the supplier to the customer” (Dainty et al., 2001). It includes the planning and management of all activities involved in sourcing and procurement and all logistics management activities, and also includes coordination and collaboration with partners, which can be suppliers, third-party service providers, and customers. It comprises various parties which perform different parts of the whole project, and poor performance by one of them will influence the next party (Kanji & Wong, 1998).

Improvement approaches such as supply chain management, which are typically associated with other industries such as manufacturing have been introduced into the construction industry. One key difference is that the fragmentation of the construction supply chain makes the innovations created by these techniques difficult to take advantage of (Blayse 2014). In the construction industry, SCM is not yet a mature subject (Manley, 2014, O'Brian, 2010), as although there has been research addressing transportation and inventory in the construction industry, usually these issues have been studied in only one tier of the supply chain. With a few exceptions of trying to incorporate SCM strategies for construction companies or projects, the opportunities for improvement by applying the SCRM concept in construction have not been explored because of the natural differences between manufacturing and construction.

According to AbouRizk et al. (2008), most of the construction industry research on supply chain risk management (SCRM) has only described the problems and challenges, and has rarely focused on analyzing and quantifying the effects of using SCM techniques on construction projects in the real world. According to their study of the literature, AbouRizk et al. (2008) reported that supply chain risk is the topic most addressed by the majority of the articles, as shown in Table 1.1. Although these articles comprised the largest percentage among risk studies, they have mainly used qualitative approaches rather than quantitative.

Table 1.1: Percentage of Articles According to Risk Type (Adapted from AbouRizk et al., 2008)

Type of Risk	Percentage of articles in the literature
Strategic Risk	20%
Operations Risk	33%
Supply Chain Risk	47%

Risk management is a powerful strategy for project planners to analyze the risks related to a project (Caddell, 2004). By understanding project risks, decision-makers can avoid, mitigate, or plan for possible negative impacts on cost and schedules, and they can capitalize on potential opportunities. By managing risks effectively, project teams are in a better position to take advantage of minimizing threats related to their projects (Molenaar et al., 2006).

Throughout the project development process, risk management can help clarify alternatives, develop strategies to prioritize and address risks, generate cost/benefit information, and handle risks in the most effective way possible. All of these actions will eventually aid the project in better meeting its goals. Risk analysis is generally accepted as a process that can be used to understand uncertainty in the project development lifecycle, and is defined as one of the main processes for project management (Project Management Institute, 2000). Risk analysis involves identifying risk events or factors that could potentially affect the project and its delivery, quantifying those risks, and developing mitigation strategies to help ensure project success.

In this research, the focus is on risk quantification (the determination of probability and impact) in support of efficiently managing supply chains in construction projects, which is a major issue that greatly affects project time and cost (Chen et al., 2010). Although a supply chain is a complex process that needs careful risk assessment, a study by Aloini et al. (2011) of 140 articles published between 2000 and 2011 reported a lack of research using quantitative approaches in construction supply chain risk management. Vrijhoef and Koskela (1999) also reported that in the construction industry, the development of supply chain models is behind other industries, because the construction industry lacks systematic supply chain designs. Often in construction projects, late supply of materials can lead to extensive delays that cause large overruns, ruining the profit margins of the projects (Russell, 2005).

While many approaches have been tried in studying SCs in construction, including risk effects, based on the author's best of knowledge, no study has addressed the dynamic updating of the probability of risk events throughout the construction life cycle to effectively study the impact on project time and cost. In order to reduce the impact of unseen risk factors that may affect the progress of any construction project, it is important to have tools to predict the influence of major risk factors in advance. However, risk factors keep changing in their probabilities and impacts along a project's duration, and these changes will be more severe and have more influence if recognized later rather than earlier, and will be harder and more costly to manage. Therefore, in order for better risk management, this research is aimed at helping to recognize the occurrence probabilities of risk factors during the early stages of a project.

1.2 Research Motivation

A key challenge in CSCM is the fact that risk factors keep changing in probabilities and impacts along supply chain life cycles. These changes will be more severe and have more influence if recognized late, and will be harder and more costly to manage. Thus, the main goal of this research is to develop a framework to automatically detect and adjust the probabilities of supply chain risk factor occurrence during a supply chain life cycle and estimate the resulting impacts on cost and schedule. This research was motivated by the following concerns:

Importance of Supply Chain in the Construction Industry

According to Briscoe and Dainty (2005) and O'Brian et al. (2009), supply chain management is important to improve the performance of construction projects. SCM has proved to be an essential management strategy when managing projects that involve a large number of participating companies, supply components, and materials (Dainty et al., 2007). Therefore, an effective SCM is a key element for reducing costs and delays in construction projects.

Need to Dynamically Update Construction Supply Chain Risks

The construction industry is a complex industry that involves different stakeholders and includes many key activities. Because of its complexity, its supply chains are very complex too, and involve different risks and uncertainties that can lead to major problems for projects (Childerhouse & Towill, 2004). Because the supply chain life cycle can be long (spanning from design to manufacturing, transportation, and delivery), different risks apply in each phase. The risks for each phase need to be identified and quantitatively assessed, and the risk level evaluated frequently to dynamically adjust the supply chain process. Currently, no research exists that looks at the risks involved through the entire supply chain life cycle. The problem is that most studies in the area of construction supply chains have been qualitative (Davis, 2008; Karim et al., 2006; Green et al., 2005), and therefore, there is a need to dynamically quantify the risk factors in order to manage supply chains effectively and efficiently.

Need to Accurately Quantify Risk Impacts on Project Time & Cost

Many studies have identified that the construction supply chain risk management literature is mainly general and descriptive (Ballard, 2000), and less attention has been given to the risk treatment and risk monitoring phases. Abourizk (2008) reported that the research on quantifying the benefits of implementing supply chain management is very limited, and therefore, there is a need for models to quantify the impact of supply chain uncertainty and important strategies on construction project time and cost, which are key performance indicators for any project.

1.3 Research Objectives and Scope

The main objective of this research is to build models that can automatically detect changes in the risks in a construction supply chain and then quantify their impact on construction time and cost. This aim is intended to assist project managers and decision-makers in understanding the key risk factors and the impact of risk-level changes on the progress of construction projects in order to facilitate warning signs and corrective actions. The detailed objectives are as follows:

1. Identifying key risk factors that apply to each supply chain phase, and creating a Risk Register with default probability distributions for these factors
2. Developing an automatic mechanism for detecting the changes in risk probability in the identified Risk Register among the supply chain processes

3. Developing a simulation model that considers the combined uncertainty in the risk factors and quantifies their impacts on project time and cost
4. Experimenting with the developed model on an industrial construction project
5. Suggesting guidelines for better supply chain management in order to handle risks

The research scope is limited to industrial projects, and focuses particularly on the major tasks that require efficient supply chain management such as the manufacture and transport of pipe spools to remote sites.

1.4 Research Methodology

As shown in Figure 1.1, the methodology that will be followed to achieve the research objectives is described as follows:

1. An extensive literature review of:
    - The importance of a supply chain in construction
    - Life cycle of a construction supply chain
    - Obstacles to a supply chain in construction management
    - Different methods of quantifying risk in a supply chain
    - Factors affecting the progress of a supply chain
    - Risk factors and construction productivity
2. Determine the key risk factors in a construction supply chain, and identify the life cycle
3. Categorize construction supply chain risk factors according to life cycle
4. List all possible automated detection models for probability changes for each category/stage
5. Design a suitable probability detection model for each category/stage of a supply chain life cycle, including:

- Delay probability model
- Economic feasibility probability model
- Supply chain visibility model for construction/ fabrication stage
- Weather and traffic model for transportation stage
- Visibility models for site storage

6. Investigate the impact of risk factors on the progress of a supply chain life cycle
7. Develop a construction SC risk register with changing probabilities and impacts
8. Develop a Monte Carlo simulation model to quantify the impact of CSC chain risk factors on a construction project's time and cost using the developed risk register
9. Develop a sensitivity analysis scheme to experiment with different scenarios
10. Propose guidelines with solutions to mitigate/reduce some of the major risk factors

1.5 Thesis Organization

The remainder of the thesis and the details of each chapter are as follows: Chapter 2 provides a brief review of the background topics and the associated literature pertinent to this research. Chapter 3 presents the proposed framework for an automatic detection mechanism for risk factors that influence the supply chain life cycle phases. Chapter 4 explains the economic and environmental models for detecting the supply chain risks in order to enhance risk management by helping decision-makers recognize the probability of the occurrence of risk factors during the early stages of a project, based on dynamic risk factor variation. Chapter 5 describes the proposed supply chain visibility model for better tracking the progress of materials in order to support efficient supply chain management. Chapter 6 summarizes the research and its contributions, and offers suggestions for future work.

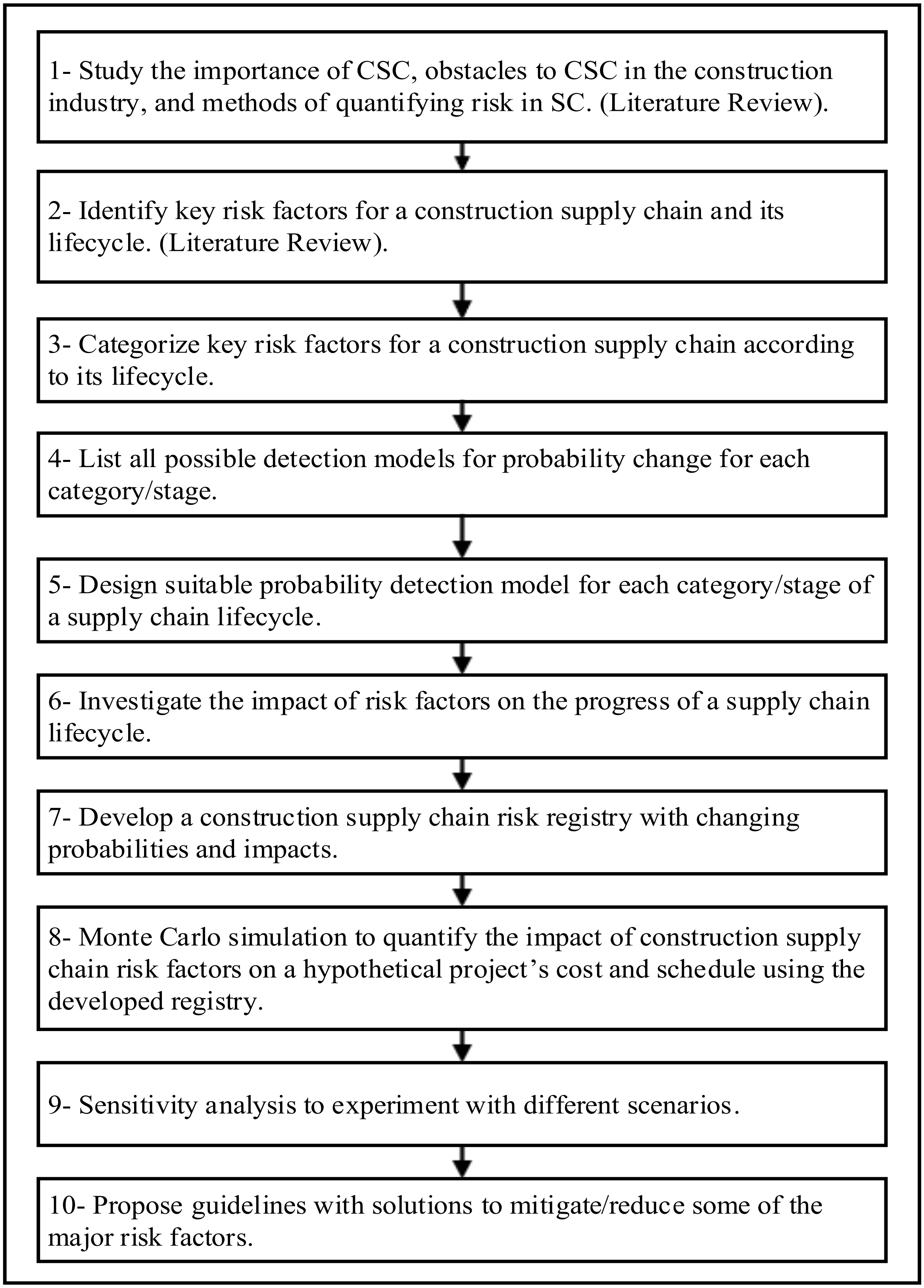


Figure 1.1: Research Methodology

Chapter 2: Literature Review

2.1 Introduction

This chapter reviews the existing literature to provide background and to review previous methods to justify the need to develop automated models for risk quantification and updates in construction projects. Previous efforts are highlighted with respect to: uncertainty in construction projects; challenges for the construction industry; risk management practices; construction supply chains (CSCs); existing CSC models; and uncertainty analysis methods (e.g., Monte Carlo simulation). The chapter concludes with the recommendation of further steps to be developed based on the current state of research in risk analysis of supply chains.

2.2 Construction Industry

The construction industry is a very significant component of the United States (U.S.) economy. As of 2014, it accounted for 9,552,000 jobs, or 6.9% of all workers (Bureau of Labor Statistics, 2014). The industry also had an output of $860.6 billion in 2014, which accounted for 4.4% of the entire U.S. economic output (Bureau of Labor Statistics, 2014). While construction in the U.S. is a large component of the economy, it still faces several significant challenges that affect the economic side of the projects. Over the years, improvement approaches such as the lean approach, total quality management (TQM), and supply chain management, which are typically associated with other industries such as manufacturing, have been introduced into the construction industry.

The construction process is very sensitive to various uncertain variables such as weather changes, breakdown of equipment, labour deficiencies, and delayed delivery of resources. These factors are unpredictable and may lead to construction project failures (Zhang et al., 2003). However, because of the complexity of construction projects, the planner is often incapable of evaluating the combined impact of uncertainties to produce reliable project estimates (Nandakumar, 2004). Therefore, appropriate methods to represent uncertainties and automatically update and predict the effect of those uncertainties on construction processes are of great importance in effective construction planning. The uncertain variables can be represented by different methods according to their nature and the available sources of information.

2.3 Uncertainty in Construction Projects

Generally, the most common method for representing the uncertainty of variables is based on probability theory. Probability theory has been studied and applied to various areas of inquiry since the 17th century (Liu, 2002). This type of uncertainty is called randomness, and statistical analysis can be used for predicting its behavior. In practice, the probability of an event can be estimated according to the frequency of that event occurring in a number of experiments (Pedrycz, 1998). In this case, it is assumed that the variable is random and that samples of real numbers of that variable are available. However, if a sample is not large enough to be significant, and more samples cannot be obtained, it is not possible to accurately estimate the event's probability.

To consider the impact of uncertainty, risk analysis is usually performed on construction projects in order to identify potential issues ahead of time and to consider contingencies. For this purpose, the effects of different uncertain factors on the productivity, cost, schedule, etc. are estimated. Simulation is a method for risk analysis in construction projects, and Monte Carlo simulation is a method for estimating the effect of random variables on complex problems using computer programs (Liu, 2002). Furthermore, discrete event simulation can be used to analyze the sensitivity of dynamic schedule and resource constraints to unexpected construction scenarios, while a Monte Carlo simulation is applied to a model that does not depend on time.

Since construction projects are usually complex in nature, simulation methods are extensively used in construction management for risk analysis of projects in which all uncertain variables are random (Ahuja & Nandakumar, 1984).

Changes are the main source of uncertainty in construction project planning, and are inevitable in most construction projects. Change is any variation to a plan. Many researchers have defined change as any event that results in a modification of the original scope, execution time, cost, and/or quality of work (Ibbs & Allen, 1995; Hanna et al., 2001; Revay, 2003). Change can be positive or negative. Positive change benefits a project by saving on cost, time, or improving the quality or scope of work. However, negative change causes deterioration to project outcomes.

Many researchers have studied the cause and effect of changes in construction projects (Arain et al., 2004, Clough & Sears, 1994; O'Brien, 1998; Ibbs & Allen, 1995; Chappell & Willis 1996; Sanvido et al., 1997; Gray & Hughes, 2001; Wang, 2000; Fisk, 1997; Dell'Isola, 1982; Geok, 2002; Thomas & Napolitan, 1995; Arain, 2002; Chan et al., 1997; Hsieh et al., 2004; Wu et al., 2004; Arain et al., 2005; Hanna, 2001; Bower, 2002). Many hypotheses have been proposed and tested to identify the factors and measure their impacts on project plan deviation.

Riley et al. (2005) examined the effects of delivery methods on the frequency and magnitude of changes in construction. Gkritza and Labi (2008) showed that increased project duration increases the chance of cost overruns. In a study of 31 high-rise projects in Indonesia, Kaming et al. (1997) found that design change is one of the most important causes of time overruns. Moselhi et al. (2005) studied the impact of change on labor productivity by looking at 117 construction projects in Canada and the US. Acharya et al. (2006) identified changes as the third-most-important factor in construction conflicts in Korea. Assaf and Al-Hejji (2006) studied 76 projects in Saudi Arabia, and they found changes to be the most common cause of delays identified by all parties: owner, consultants and contractors. Changes in construction projects are documented in the form of change orders.

2.4 Risk Management in Construction Industry

According to the Project Management Book of Knowledge (PMBOK), risk analysis involves the following processes, which are briefly discussed in the following sections, as shown in Figure 2.1:

1. Risk Management Planning
2. Risk Identification
3. Qualitative Risk Analysis
4. Quantitative Risk Analysis
5. Risk Response Planning
6. Risk Monitoring and Control

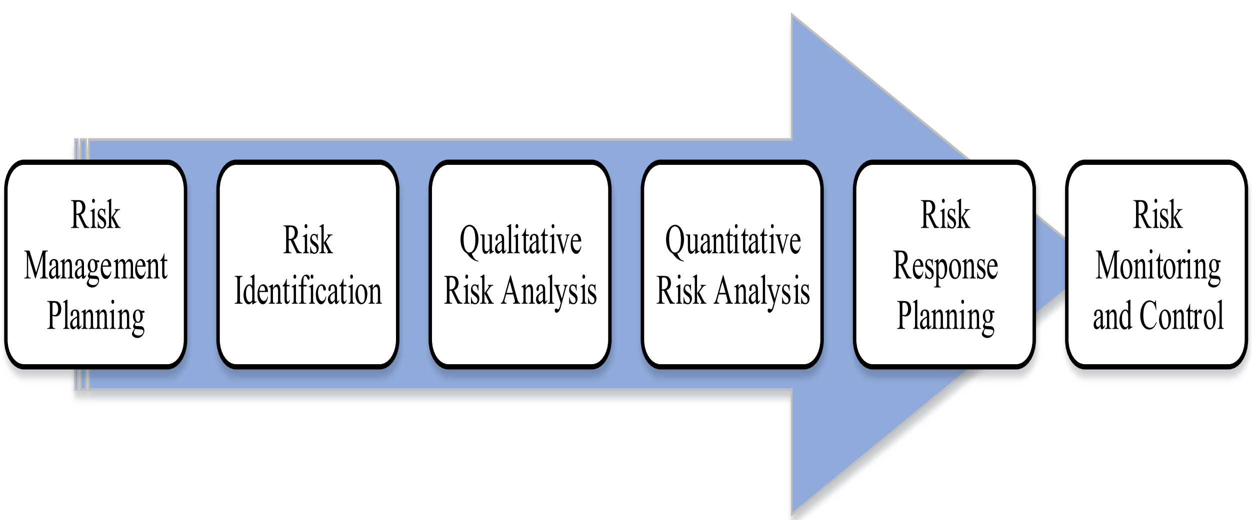


Figure 2.1: Risk Management Process Flow Adapted from (PMBOK, 2014)

This process flow has clear objectives to decrease the probability and impact of events that could delay project delivery and/or create a budget overrun.

Risk management planning. The risk management process in construction begins with risk management planning; this phase outlines the strategy for achieving the objectives and goals for the process. During this phase, owner objectives, scope, and risk criteria are outlined. It is important to consider both the external environment (e.g., political, economic trends, and external stakeholder input) and internal environment (e.g., an organization's expectations and risk tolerance) to understand the overall project expectations (ISO, 2009). The project charter, risk management policies of the given party, roles and responsibilities, and the work breakdown structure, among other processes, are thoroughly investigated during this phase (Project Management Institute, 2000, p. 129). It is imperative to understand the unique intentions, requirements and risk tolerance level of the given party for each project. The result of the risk planning phase is a document consisting of the risk management plan. This plan summarizes the information gained during this phase and creates an outline of the key plans and steps to follow for the remainder of the process.

Risk identification. Once the risk management plan is in place, the risk identification phase can begin. Ideally, during this process, key project personnel, the risk management team, and experts in the area (both those affiliated with the project and not affiliated) attend a brainstorming session where all possible project risks can be recorded. During these brainstorming sessions, all risks should be incorporated, including those related to quality of work, efficiency, cost, and schedule (Al-Bahar & Crandall, 1990). This can then be supplemented with historical information from similar projects, especially documented projects consisting of lessons learned. Risks identified can be organized in terms of categories that best suit the given project, and the categories should strategically unify certain risks and help with the subsequent stages of risk management. The Project Management Institute (2000) provided examples of such categories, including "project management risks, organizational risks, and quality risks" (Project Management Institute, 2000). The risk identification process is ongoing for the duration of the project. As uncertainty decreases, such as when a project design becomes complete, the risks will become clearer. Risks should be adjusted constantly in the project.

Qualitative risk analysis. Qualitative risk analysis refers to when risk factors are analyzed in terms of their likelihood of occurrence on a project and the impact this occurrence would have on the project if the risk were to occur. These factors are examined in the qualitative phase in terms of verbal expressions. This method lends itself best when utilizing expert opinions, as verbal expressions are often innate and understood by the general population. By examining each identified risk, the risks can be better understood. The quality of each risk determined in the risk identification phase can be assessed, and some may be omitted. Risks can be organized in terms of importance based on the assessed impact and available methods of mitigation for a given risk.

The first level of quantification described by the Construction Industry Institute (CII) involves enumerating the risk factors (or events) and then quantifying them by subjectively ranking them in terms of importance. The higher-ranked risks are then mitigated and managed on the project. Specialized tools and methods have been developed to examine risks in this way, and one such commonly used tool is the risk rating matrix (AbouRizk, 2009). This matrix combines the probability and the impact in order to understand the severity of the risk and the actions that should be taken. For example, if a risk is very likely to occur and the impact would be disastrous, this would mean that the risk is intolerable for the project. Measures would either have to be taken to eliminate this risk, or the project might be terminated, depending on the risk tolerance of the decision-maker. While some parties are willing to take a great deal of risk, others may draw the line much sooner. Once a qualitative assessment of risks has been completed, there is generally a good understanding of the most important risks that will affect the project.

At this point, certain decisions can be made. Based on analysis it is known that most risks occur in one particular location of the project. Redesign of this area may be a possibility and could be investigated. Likewise, a different method of construction may be chosen based on the number of risks impacting the project. In order to gain a further understanding of the cost and schedule impacts that risks will have on a project, quantitative analysis usually follows.

Quantitative risk analysis. Quantitative risk analysis (QRA) uses the results determined during qualitative analysis and turns them into quantifiable information that can be useful for the project. This is generally done by assigning probability and impact scores to the verbal expressions and multiplying them together in order to gain a value for risk severity (Construction Industry Institute, 2012). Quantitative analysis can occur for both costs and scheduling. Quantitative analysis of schedules can be performed using techniques such as Project Evaluation and Review Techniques (PERT) analysis or Monte Carlo Simulation of CPM networks. Quantitative analysis of cost utilizes the work breakdown structure, an analysis of the estimate often using Monte Carlo simulation, or other analytical techniques. Galway (2003) found that the common consensus among users of risk analysis is that it is valuable and desired. Still, empirical studies appear to be almost nonexistent in this area.

Risk response planning. Based on the established risks, risk response planning involves determining the optimal method of mitigation (Project Management Institute, 2000). Response planning may directly follow the qualitative phase, or continue after quantification. This depends on what is defined in Phase 1 (risk planning), as goals will vary based on the project. The risk-response planning phase involves determining how to avoid a risk; for example, changing portions of the design or undertaking a new process, which can help to reduce a risk. Such methods are usually derived through a workshop setting and conducted in a hierarchical manner (with risks most dangerous to the project being addressed first). Historical data can also help to determine the most effective ways to avoid a risk.

Risk monitoring and control. Risk monitoring and control, the final phase in risk management, involves continual inspection, examination, review, and observation in order to determine if any changes or unexpected outcomes have occurred and ensure that the established goals are being met (ISO, 2009). This is often done by having a designated individual or group of individuals who are dedicated to checking on the process through interviews with the appropriate people, on-site checks, consistent reporting, and thorough documentation of events.

2.5 Construction Supply Chain (CSC)

2.5.1 CSC Concept and Characteristics

A construction supply chain differs from a manufacturing and fabrication supply chain in the way it is organized. In mass production, material moves from station to station, and workers perform the necessary steps to assemble the final product (Lamming, 1993; Womack et al., 1990), differently from construction, where the product is fixed and the workers move around the product (Ballard & Howell, 1998). In the manufacturing industry, standardization of parts and component-assemblies has paved the way for the creation of a separate industry that specializes in the production of these parts and components and sells them to the manufacturing industry. In other words, the “supplier” became an independent company (Lamming, 1993; Womack et al., 1990).

A construction supply chain can be regarded as “fixed position manufacturing, in which the product being manufactured eventually becomes too large to be moved through work stations, so the work stations (work crews) have to move through the product. Construction, shipbuilding, and airplane manufacturing belong in this category” (Ballard & Howell, 1998). Unfortunately, there appears to be little written on fixed position manufacturing. The actual design and construction of a facility is typically executed by a general contractor and sub-contractors, but fabrication of certain products from raw materials such as fabricated pipes, structural steel, concrete, and rebar is most likely provided by a third-party supplier (Tommelein & Weissenberger, 1999).

Even if construction projects and their supply chains are one-of-a-kind, temporary organizations, there are still several characteristics that do not change drastically from project to project in terms of how these characteristics can be controlled. To illustrate this point, Vrijhoef and Koskela (2000) devised “the four roles of supply chain management in construction”, which highlight different arrangements between the project site, immediate suppliers, and/or the extended supply chain of construction projects. These four roles reflect the interaction between the supply chain and site activities with the purpose of clarifying the roles and possibilities of SCM in the construction industry (Vrijhoef & Koskela, 2000). The four roles are described as follows:

- Improving the interface between site activities and the supply chain: This goal is to reduce the costs and duration of site activities. In this case, the primary consideration is to ensure dependable material and labour flows to the site to avoid disruption to the workflow. This can be achieved by simply focusing on the relationship between the site and direct suppliers.

- Improving the supply chain: The focus is on the supply chain itself, with the goal of reducing costs, especially those relating to logistics, lead-time, and inventory. Material and component suppliers may also adopt this focus.
- Transferring activities from the site to the supply chain: The focus is on transferring activities from the site to earlier stages of the supply chain. The rationale may simply be to avoid inferior conditions on-site, or to achieve wider concurrency between activities, which may not be possible with site construction with its many technical dependencies. The goal is again to reduce the total costs and duration. Suppliers or contractors may initiate this focus.
- Integration of site and supply chain: The focus is on the integrated management and improvement of the supply chain and site production. Thus, site production is subsumed into SCM. Clients, suppliers, or contractors may initiate this focus.

2.5.2 Factors Affecting Construction Supply Chain (CSC)

Kumaraswamy and Thomas (2003) conducted a thorough study of the construction supply chain. They carried out their research from the interesting point of view of highlighting the major problems in construction and trying to propose a framework for SC concept implementation, instead of seeking in isolation for different issues. They characterized the weak links of the construction supply chain as follows:

- Adversarial relationships between clients and contractors
- Inadequate recognition of risk and benefit sharing
- Narrow-minded win-lose attitudes

• Power domination and contractual commitment problems.

• Inadequate information exchange and restricted communication

• Minimal or no direct interaction

They also identified factors related to cultural differences that can directly or indirectly affect the construction supply chain, and finally proposed a conceptual framework for the supply chain consisting of driving forces that can lead the industry toward relational contracting. Tommelein, Akel, and Boyers (2003), in another construction supply chain study, investigated a construction company's tactics as a case study. In an interesting study on construction supply chains, Walsh, Hershauer, Tommelein, and Walsh (2004) modeled a project supply chain and showed the potential gains of applying such a concept in a construction environment.

Another study done by Gosling et al. (2013) showed a list of possible SC risk factors plotted against the impact and likelihood values (as shown in Fig. 2.2). Through analysis of the clustering in the positioning matrix, it can be concluded that overall, the results support that all parts of the supply chain lifecycle should be considered for risk likelihood and impacts.

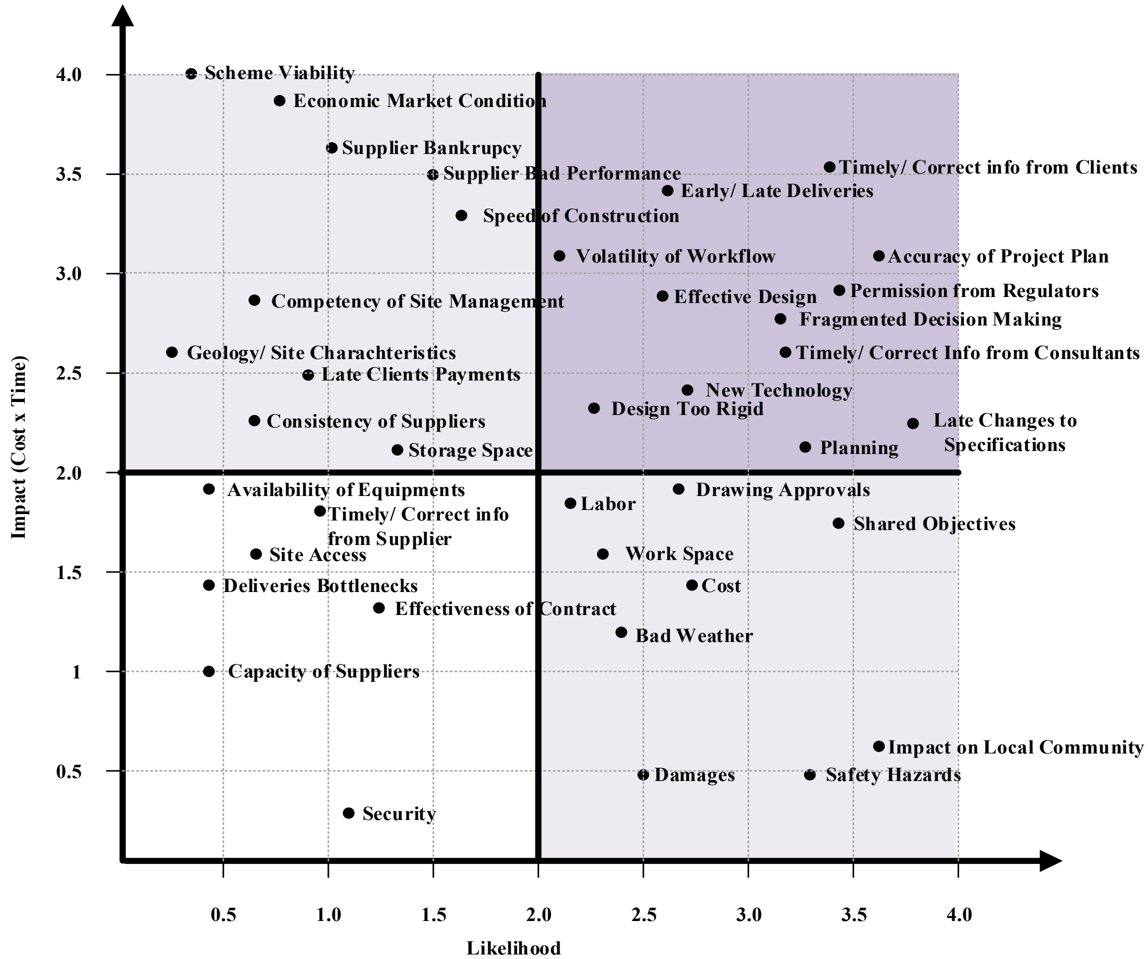


Figure 2.2: Risk Matrix for CSC with Impact and Likelihood adapted from (Gosling et al., 2013)

2.5.3 Research on Supply Chain Visibility (SCV)

Supply chains are nonlinear dynamic systems, which are complicated by long, variable delays in material and information flows. Traditional supply chains are rapidly evolving into dynamic trading networks comprised of groups of independent business units sharing planning and execution information. While a great deal of research is underway to improve efficiency in supply chains, manufacturing companies are also looking for better ways of getting their products to customers in a more timely and cost-efficient fashion. An improved manufacturing process might fail to achieve a benefit for the company if the product manufactured is not available in the right place at the right time. At the same time, excessive stock raises inventory costs and the likelihood of the product becoming outdated. For the abovementioned reasons, companies feel a need for visibility regarding the appropriate information in a product distribution network as well as real time information updates to optimize planning costs and scheduling.

Visibility is the ability to access and share information across a supply chain and to use it in real time (Lamming et al., 2001). Visibility across a supply chain is a key element in supply chain competition, and all businesses in a given chain should have access to updated information and performance figures regarding the main processes of their partners. As global supply chains compete in an increasingly complex and rapidly changing business environment, supply chain responsiveness has become a highly prized capability. Supply chain visibility is key for at least three reasons. First, it helps supply chain managers to improve their operational efficiency (Smaros et al., 2003); for instance, good visibility for suppliers prevents the effect of stock-outs (e.g., the shutdown of an assembly line due to shortage of a component) and increases resource productivity (e.g., the handling costs of incoming materials). Second, visibility can improve the effectiveness of the planning process (Petersen et al., 2005), reducing inventories and safety lead-times and increasing delivery promptness and accuracy, which are dramatically affected by the performance of the suppliers. Finally, visibility is an enabler for effective knowledge exchange and better governance.

Supply chain visibility is defined as access to high quality information that describes various factors of supply and demand. In order for information to be of high quality, it must be accurate, timely, complete, and in a usable form. Achieving a high level of supply chain visibility requires the acquisition of multiple types of high-quality supply chain information. Researchers have argued that organizations need visibility with regard to supply chain processes and supply characteristics (Barratt & Barratt, 2011). To increase responsiveness, supply chain managers often seek information that provides greater visibility into factors affecting supply and demand. Managers often claim, however, that they are awash in data but are lacking in valuable information. Taken together, these conditions suggest that supply chain visibility is necessary, but has insufficient capability for enabling supply chain responsiveness.

Several studies have attempted to quantify the value of visibility (Bailey & Pearson, 1983; Gustin et al., 1995; Mohr & Sohi, 1995; Closs et al., 1997; Kaipia & Hartiala, 2006), but have mainly focused on simplistic, linear supply chains. In contrast, this thesis aims to bridge the gap between the literature and managerial practice by providing a structured and quantitative approach to assess the visibility that a company has with regard to its supply chain. Supply chain visibility will be measured in terms of both the quantity and the quality of the information flowing between the supply chain leader and the suppliers at different tiers.

Today, companies use a variety of applications to obtain appropriate product information and for planning and optimizing the performance of their supply chains. These applications include Materials Requirement Planning (MRP), Manufacturing Resources Planning (MRPII), and Enterprise Resource Planning (ERP). Most of these applications are focused internally within an enterprise, and depend on data gathered at regular intervals from purchasing, manufacturing, distribution, and sales operations. Current techniques for gathering data include manual data entry by operators at various locations into logbooks or data-entry terminals, usage of barcodes, and tags. Transfer of information across units is usually effected by mail, phone, fax, email, or electronic data interchange (EDI). Data gathered by these techniques are typically not in real-time, and are usually updated on a daily, weekly or monthly basis. Also, there is a significant percentage of errors in manual data entry.

Different methodologies have been studied to investigate how better visibility can improve business performance (Bourland & Powell, 1996; Chen, 1998; Gavirneni et al., 1999; Chen et al., 2000; Cachon & Fisher, 2000; Li et al., 2001; Yu et al., 2001; Gavirneni, 2002; Croson & Donohue, 2003; Disney & Towill, 2003a,b; Sahin & Robinson, 2005). However, most of the studies have focused on simplified supply chains or have provided partial measures that do not consider the different dimensions of visibility. Indeed, supply chains are becoming more and more similar to supply networks, and a comprehensive measure of visibility for complex supply chains is lacking.

Ineffective materials management continues to be a leading cause of poor performance in construction projects today. Many of the problems arise as a result of an inability to convey information pertaining to the location and status of construction materials and equipment in an accurate and efficient manner. Common materials-related issues that can arise include lack of availability of required materials, inaccurate warehouse records, damaged materials or equipment due to improper storage, improperly sequenced deliveries, and large surpluses of material at project completion (Plemmons & Bell, 1995; Thomas, Riley, & Messner, 2005). The results of these issues include delays in project schedules and extra incurred costs.

In this thesis, we present a novel framework for improving the visibility of information in supply chains by reducing delays in information flows. Information visibility is identified as one of the key elements for a successful supply chain, and so we analyze the dynamics of a supply chain under different scenarios of information visibility and forecasting decisions with the help of simulations, and then propose a framework to improve information visibility in supply chains using radio frequency tags, tag readers, product identification codes, object description language, and the internet.

2.6 Management of a Supply Chain in Construction

Supply chain management (SCM) is a holistic approach that can be employed within the construction industry to drive improvement. Techniques such as sharing information with suppliers and reducing the supplier base are not common in the construction industry because of the large use and number of subcontractors and material suppliers (Wong 1999), as these entities are generally concerned with only their benefit instead of the overall goal (Vrijhoef & Koskela, 2000). In construction, SCM is not yet a mature subject. Although there has been research addressing transportation and inventory in the construction industry, usually these issues have been studied in only one tier of the whole supply chain.

With a few exceptions of trying to incorporate SCM strategies and tactics into construction companies or projects, because of the natural differences between manufacturing and construction, the improvement opportunities of applying the SCM concept in construction have not been explored. Jiang and Issa (2005) recommended two methods of modeling CSC performance management. They identified supply chain performance drivers in construction and set a series of key performance indicators. They modeled the supply chain of a residential construction company and tried to measure its supply chain performance.

Vaidyanathan and O'Brien (2005) tried to explore opportunities for IT implementation in the construction industry. They studied the supply chain concept and methods in manufacturing and construction comparatively, and also investigated IT tools used in the construction industry. They reviewed implementation experiences in order to find out the challenges in the construction supply chain, and made some recommendations based on their findings. Cox and Ireland (2002) studied different aspects of the UK construction industry in order to provide a better understanding of its supply chain. They mapped the industry supply chain, reviewed best practices, and tried to provide a better way of thinking regarding problems in the UK construction industry.

2.7 Supply Chain Modeling

Most of these modeling approaches for CSC address two main issues, or an integration of them (Chen & Paulraj, 2005): production planning and inventory control, and distribution and logistics. The early analytical modeling approaches for SCM were deterministic models, while many recently developed models have more than one unknown variable following a particular probability and statistical distribution. Because of the high complexity of the models and the large number of decision variables involved, it is computationally very difficult to find the optimal solution in modeling a real supply chain. Simulation methods have been widely utilized as a way of dealing with such complexity and uncertainty.

As a summary of all literature effort and models related to CSCM, and in addition to what have been discussed earlier, Table 2.1 describes the prominent effort and comments on technologies and drawbacks. Further comparison and distinction between the analytical and simulated modeling of supply chains has been done by Chatfield (2001). Simulation studies of supply chains are often referred to as descriptive models because the developed simulation models have not so far provided any optimal solutions.

Table 2.1: Summary of Models Related to Construction Supply Chain

Reference	Description	Comment
(Young et al., 2011)	Integration of automated material locating & tracking technology (RFID, GIS) and CSC networks	Did not consider the risk factors impacting the CSC network within the study
(Chang & Makatsoris, 2001)	The importance of supply chain simulation modeling in supply chain management using discrete event simulation	Generic model and doesn't apply for construction industry, no case study used for validation
(Jung et al., 2004)	computational framework using deterministic models for safety stock levels in supply chain management	Limited to safety stock levels in industrial SC and used deterministic planning and scheduling models
(Kang et al., 2013)	Risk management visualization system to analyze risks using fuzzy and AHP integrated with 4D CAD system	Used seven risk factors and no dynamic updates are available and need to be validated numerically
(Lee et al., 2002)	A combined discrete and continuous model for supply chain simulation	Simple industrial SC simulation, didn't count for risk events impacting time and cost, no automatic update
(Risku & Karkkainen, 2005)	Shipment Tracking based-Approach for managing the material logistics of construction projects	Needs more case studies for validation using SC visibility for materials and no economic impact done
(Ebrahimy et al., 2011)	Quantitative analysis using simulation approach to study variables affecting productivity in a construction project	Limited numerical results and lacks for detailed and efficient simulation model of the whole SC cycles
(Aloini et al., 2012)	Review of 140 articles to analyse development of SCM and investigate risk factors of SCM in construction	lacks of risk quantification and assessment methods and lacks for empirical case studies
(Angerhofer & Angelides, 2000)	Applying System Dynamic Modeling in supply chain management	Lacks for theoretical models for validation and limited to industrial sector
(Vilko & Hallihas, 2011)	Monte-Carlo simulation to identify risks affecting SC to analyze the impact of the risks in terms of delay.	Analysis rely on expert knowledge and subjective assessment, lacks for empirical & financial impact
(Vidalakis et al., 2010)	A conceptual logistics model facilitating experimentation using simulation modelling of construction supply chains	Model needs to be validated using wider samples and limited to inventory, transportation costs.
(Gosling et al., 2013)	Identification and categorization of uncertainty using empirical and multiple data collection methods	Theoretical approach and needs case studies and numerical methods for verification
(Vlachos et al., 2006)	Development of a SD-based model for remanufacturing and capacity planning of a single product supply chain	More scenarios needed for identifying efficient policies and limited for material recycling systems
(Phillips et al., 2009)	Quantification system based on fuzzy set and probability theories combined with total Uncertainty algorithm	Uses Conceptual case study and no validation for the models.
(Assaf & Hejji, 2005)	Survey on time performance of different projects to determine the causes of delay and their importance	Limited to one location and specific type of construction projects and lacks for financial impact
(Pan et al., 2011)	Analysis and design of CSC models for procurement and processing using SCOR Model and SD software	Data of the performance metric needs to be input manually
(Kumaraswamy & Chan, 1996)	System dynamic for dynamic planning and control to support strategic and the operational project management	Lacks for case studies on construction projects and needs more effort to reach an optimum framework
(Pujawan & Geraldin, 2009)	House of risk (HOR) framework to manage SC risks and reduce the impacts of the risk events	No correlations between risk events and most of the cost entries based on subjective judgment
(Tse and Tan, 2011)	Using a supply chain quality risk management framework, integrated with the SC marginal analysis	Focus only on issues of analyzing the product quality risk and visibility in global supply chain
(Caridi et al., 2010)	Inbound quantitative supply chain visibility model to assess the degree of visibility in complex supply networks	Lacks for empirical evidence for validation, applicable only on industrial sector
(KeiTse et al., 2011)	Developing of supply chain risk management (SCRM) framework to reduce the quality risk	Need to be empirically validated and other areas than quality management are missing
(Meng, 2011)	Surveys to identifying characteristics of SC relationships in construction and impact on project performance	No empirical data to study influence of relationship management on project performance
(Love et al., 2001)	Systems dynamics SD model and a case study to describe the major factors influencing a project's performance	Focus on Construction projects and lacks of actual case study
(Anne-Decelle, 2005)	Simulation methods to study SC communications in manufacturing and how it applies to construction	No Case Studies available and needs more detailed presentation of the results of the project

Simulation models have been employed to gain insight about a certain supply chain's structure or to compare different strategies in the supply chain. Other descriptive models of supply chains are:

- Forecasting models, which focus on predicting important factors for production such as demand rate, price, or raw materials cost, based on historical data
- Cost relationships, which describe how different factors influence direct and indirect costs
- Resource utilization relationships, which address resource allocation and utilization in different production activities

Researchers have categorized supply chain models in different ways. The most common categorization is to divide these models into two sets: (1) deterministic analytical models; and (2) stochastic analytical models:

Deterministic Analytical Models. This class of supply chain model includes the models in which all variables are known and specified and there is no uncertainty associated with them. This type of model can be found mostly in older literature, and some examples of such models are reviewed in this section. Newhart, Statt, and Vasco (1993) tried to design the supply network of a company making corrosion-resistant steel coils. They used a two-phase approach to design an optimal supply chain to evaluate four different scenarios of placing different parts of the supply network in different locations. The objectives in their mathematical model were to maximize total profit, minimize total access time for customers, and maximize the aggregated location incentive.

Stochastic Analytical Models. This category of model contains the models with some non-deterministic variables. These variables are normally assumed to follow a certain statistical distribution, so there are uncertainties associated with such variables. Some instances of this class of model are surveyed in this section. Simulation models in general can accommodate both deterministic and stochastic variables.

Supply chain simulation models include models designed to solve a specific problem as well as models or software constructed to allow users to develop their desired supply network with a variety of structures. The scope of the simulation models is determined based on the processes the model is able to address some supply chain processes are: demand and sales planning, inventory planning, distribution planning, and production planning. The supply chain simulation models reviewed by Terzi and Cavalieri (2004) were all developed to address a specific problem for a specific network structure.

Some of the most recently developed supply chain simulation models of this type are reviewed in the following. Tiger and Simpson (2003) used discrete event simulation to design the supply network of a multi-billion-dollar technology-based company with more than half of its market in the Asia-Pacific region. Several sources of complexity in the problem and a substantial need for flexibility and real-time analysis made the authors choose discrete event simulation as a practical way of dealing with such a complicated problem. Warng, Chong, Xie, and Burgess (2005) used simulation in order to investigate the effects of several assumptions regarding simplification of demand patterns and lead times in a wide variety of supply network structures. They analyzed four different coordination policies and measured the benefits gained for each party involved in the network in terms of average stock level, backorder level, and cost.

Simulation is a very powerful tool for modeling real-life situations. Due to the unreliable environment and the complex process in construction projects, simulation has been proposed as an indispensable problem-solving methodology for analyzing construction processes (Halpin & Riggs, 1992). For example, Monte Carlo simulation is applied to a model that does not depend on time, and in the following section, a brief background on Monte Carlo simulation is provided.

2.8 Monte Carlo Simulation

The Construction Industry Institute (CII, 2012) outlined the risk process in terms of three levels. The third level requires detailed analytical techniques such as Monte Carlo Simulation (MCS) modeling. This is generally referred to as quantitative risk analysis (QRA). Within QRA, each of the risk factors is quantified by estimating the probability of occurrence and the cost or schedule impact upon the risk's occurrence. In a Monte Carlo simulation, values are sampled for each of the risks for both probability and impact and combined to estimate the overall impact on the project's costs and schedule. Once a Monte Carlo simulation is complete, the project cost (or schedule) is represented with a distribution. The decision-maker then uses that distribution to determine the project's budget by accepting a certain amount of risk (CII, 2012).

Monte Carlo simulations have been used extensively for addressing probabilistic uncertainties in construction projects; for example, for estimating the duration or cost of a construction project (Ahuja et al., 1994) or for schedule risks (McCabe, 2003). Computer models can be used to predict the output of a system by abstracting its behavior. When the probabilistic information for uncertain parameters of a computer model is provided, a Monte Carlo simulation can be used to provide statistical estimations for the outputs. Probabilistic information is collected through previous experiments on a project for variables that have random types of uncertainty, which are called random variables (Ross et al., 2001).

Monte Carlo simulation is a proven technique used to simulate costs and schedules. Monte Carlo Simulation makes use of probability distributions in place of deterministic values in order to model the uncertainties associated with a particular input and the possible outcomes that can occur, thus allowing for better decision-making abilities when dealing with such uncertainties (Palisade Corporation, 2010). This technique simulates the real world by randomly selecting data from a defined distribution in order to provide the most probable distribution of the uncertain component. Monte Carlo simulation depends on statistical sampling to evaluate outcomes, and therefore the simulation experiment entails taking samples in numerous iterations. The more iterations run, the more realistic the resulting distribution will be. This is because every time an iteration is carried out, a component is randomly selected from its defined time and cost distributions.

The core of every Monte Carlo aimulation is a deterministic model that closely resembles a real scenario. This model incorporates certain mathematical relationships that apply transformation on the input values in order to produce output. Once the model has been generated, it will require a set of inputs, which will constitute the risk portion of the model. The risks originate from the stochastic nature of the input variables, and are identified with underlying distributions. Assigning the representative distributions may require extensive historical data. The input distribution can be determined through expert opinion or a variety of methods including Maximum Likelihood, Method of Moments, and Non-linear Optimization (Raychaudhuri, 2008). After the input distribution has been determined, random sample values are extracted from each distribution and used as input parameters for a single run. This process is repeated for each run, allowing the static model to generate a spectrum of output values. Six steps are needed for a Monte Carlo simulation:

1. Definition of the system using an input-output numerical model
2. Generation of random numbers
3. Generation of random variables
4. Evaluation of the model multiple times (N simulation cycles)
5. Statistical analysis of the resulting behavior
6. Study of simulation efficiency and convergence

Monte Carlo simulation performs various experiments on a model by using inputs obtained by sampling from the input probability distributions. Probability distributions define the probability of values of a discrete random variable; however, in an interval of continuous random variables, there are an infinite number of values, but the probability of obtaining any single point is almost zero. Therefore, a Probability Density Function (PDF) is defined on these variables. The PDF can be used for calculating the probability that the random variable falls into a particular interval (Equation 1).

$$\Pr(a < x < b) = \int_a^b f(x).dx \tag{1}$$

Figure 2.4 illustrates an example of a PDF and represents the probability based on the area under the curve.

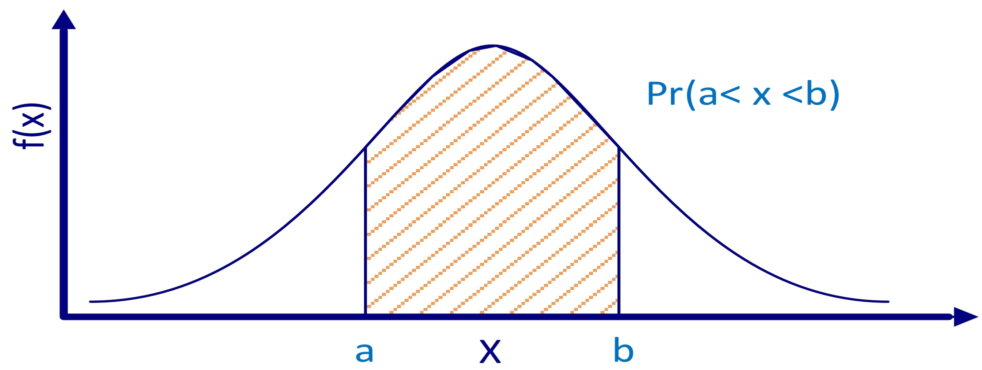


Figure 2.3: Probability Distribution Function (PDF) f(x) of Random Variable x

The Monte Carlo simulation method is used for estimating the output (Y) of a model with random input variables (X_1, X_2, X_3,…,X_n) (Figure 2.4). The process of a Monte Carlo simulation is explained in the following (Ahuja et al., 1994). This procedure is also illustrated in Figure 2.3.

1. Sample n values r_1, r_2, , $r_{n.}$ from the probability distributions of the random inputs R_1, R_2,, R_n
2. Assign the values to the model and calculate the output: $X = M$ (r_1, r_2, …, r_n)
3. Store the output *Y*
4. Repeat steps 1 to 3 for i =1 to k
5. Perform statistical analysis on the collected outputs

The number of iterations, k, depends on the level of accuracy that is required in a model. Having too few iterations results in inaccurate output, while too many iterations requires too much time to run the model. The accuracy of the model with k iterations can be estimated as the variance of required statistics (Easy Fit software). For decision-making purposes, the mean and variance of the output of a Monte Carlo simulation are the most important statistics typically calculated. If we run a simulation model for k independent times and record the output Xi (i=1, …, k), the sample mean (X) and variance (S2) can be calculated in Equations 2 and 3 respectively.

$$X = \frac{\sum_{i=1}^{n} Yi}{n} \tag{2}$$

$$S^2 = \frac{1}{n} \sum_{i=1}^{n} (Yi - Y)^2 \tag{3}$$

MC simulation is also widely used in construction due to the fact that large-scale projects have many inherent uncertainties. Each unique construction project presents its own set of challenges due to the diversity of resources and activities. As well, when a critical path model is used, Monte-Carlo simulation runs create alternate critical path that result in longer and more accurate estimates of project durations than PERT or deterministic CPM methods. Furthermore, in construction management, a decision-maker is usually interested in two important statistics: (1) an arbitrary quantile; and (2) the probability of exceeding (or not exceeding) a specific threshold. For example, one may want to estimate the completion time of a project with 95% confidence. This value is referred as the 95th quantile of the output. In the context of the simulation process, this means that 95% of the conducted simulation results are accurate with regard to the completion time for the project. Decision-makers are also interested in finding the probability that a project will exceed a certain value of cost or time (Ahuja et al., 1994).

The Cumulative Distribution Function (CDF) is typically used for finding the probability of not exceeding a given threshold. Equation 4 defines the CDF function of a random variable X (Ahuja et al., 1994). The CDF can be calculated based on PDF f(x) using Equation (4, 5).

$$Fx(x) = \Pr\{X < x\} \tag{4}$$

$$F(x) = \int_{-\infty}^{x} f(t).dt \tag{5}$$

Considering a finite number of random samples from k experiments, the CDF function can be estimated with Equation 6.

$$Fx(t) = \frac{\text{Number of Samples}}{n} \tag{6}$$

The inverse of the CDF is used for finding an arbitrary quantile. Figure 2.5 indicates the use of CDF F(x) for finding the 90th quantile of a random variable.

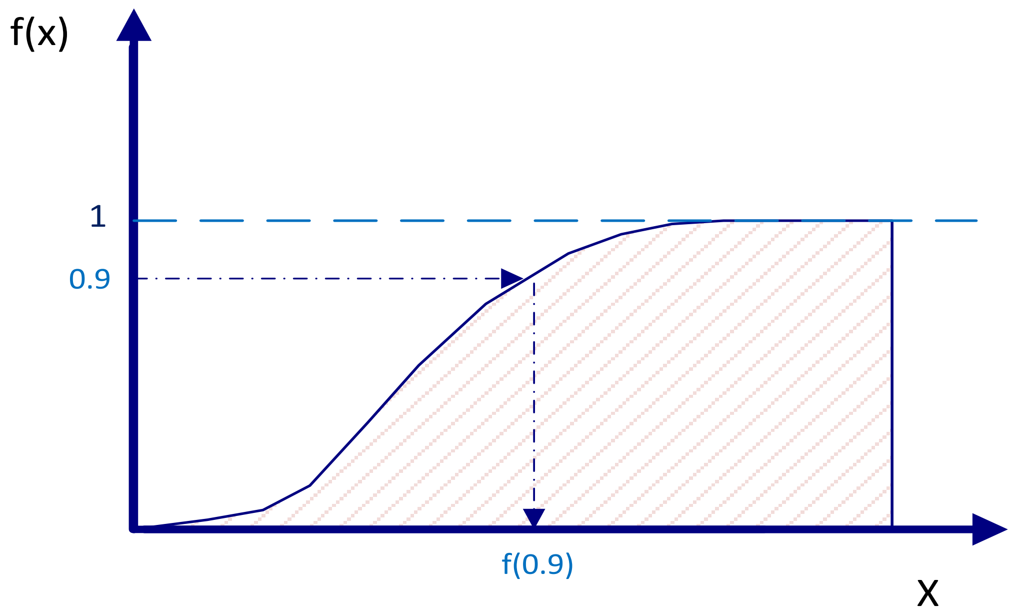


Figure 2.4: Using the inverse CDF to find the 90th quintile of random variable x

The purpose of a Monte Carlo Simulation is to derive a true probabilistic distribution for the estimated cost (or schedule) of each component of a project estimate. The nature of the Monte Carlo simulation allows the random characteristics of the cost of construction items to be modeled. This is achieved by providing numeric estimations of the uncertain features of the cost components. Each of the uncertain components of the estimates is then estimated by a probability distribution of the cost rather than as a single number. In this approach, the simulation model represents the line items in the estimate and their summation. During simulation, samples of the base values for the individual line items (or their basic parameters like unit rates or quantities) are taken and extended as required to determine the overall cost distribution of a project.

2.9 Discussion of Research Gaps

While many efforts studied supply chain in construction, including risk effects, no studies considered the dynamic updating of the probability of risk events throughout the supply chain process to effectively update the impact on project time and cost. In order to reduce the impact of unseen risk factors that may influence the progress of any construction project, it is important to have supporting tools to predict the influence of the major risk factors in advance. However, risk factors keep changing in their probabilities and impacts along a project's duration. These changes will be more severe and have more influence if recognized later rather than earlier and will be hard and costly to manage. Therefore, the proposed research helps in recognizing the occurrence probabilities of risk factors at an early stage, to enable better risk management. Building an automated probability detection framework that follows this conceptual approach is discussed in the next chapter.

Chapter 3: Framework for Automatic Detection of Changes in Supply Chain Risks

3.1 Introduction

In this chapter, the proposed framework with its conceptual approach will be introduced in detail. The framework consists of four steps; each one is explained in the following sections. The risk register step is presented to identify major risk factors that influence SCs, followed by the automated risk update step, which explain the proposed models for automatic data collection. The analysis and evaluation step using simulation models and statistical analysis tools is also presented in this chapter, and finally, the decision support step is presented as the last step of the framework.

3.2 Framework for Automatic Probability Change Detection

A key challenge in Construction Supply Chain Management (CSCM) is the fact that risk factors keep changing in probabilities and impacts along supply chain life cycles. These changes will be more severe and have more influence if recognized late, and will be harder and more costly to manage. Therefore, this research will help in automatically updating the risk register and probabilities of occurrence in order to accurately quantify the impacts on project time and cost. The proposed automated framework and its work flow are shown in Figure 3.1, with four main modules as follows: (1) Risk Register; (2) Automatic Risk Update; (3) Analysis and Simulation; and (4) Decision Support.

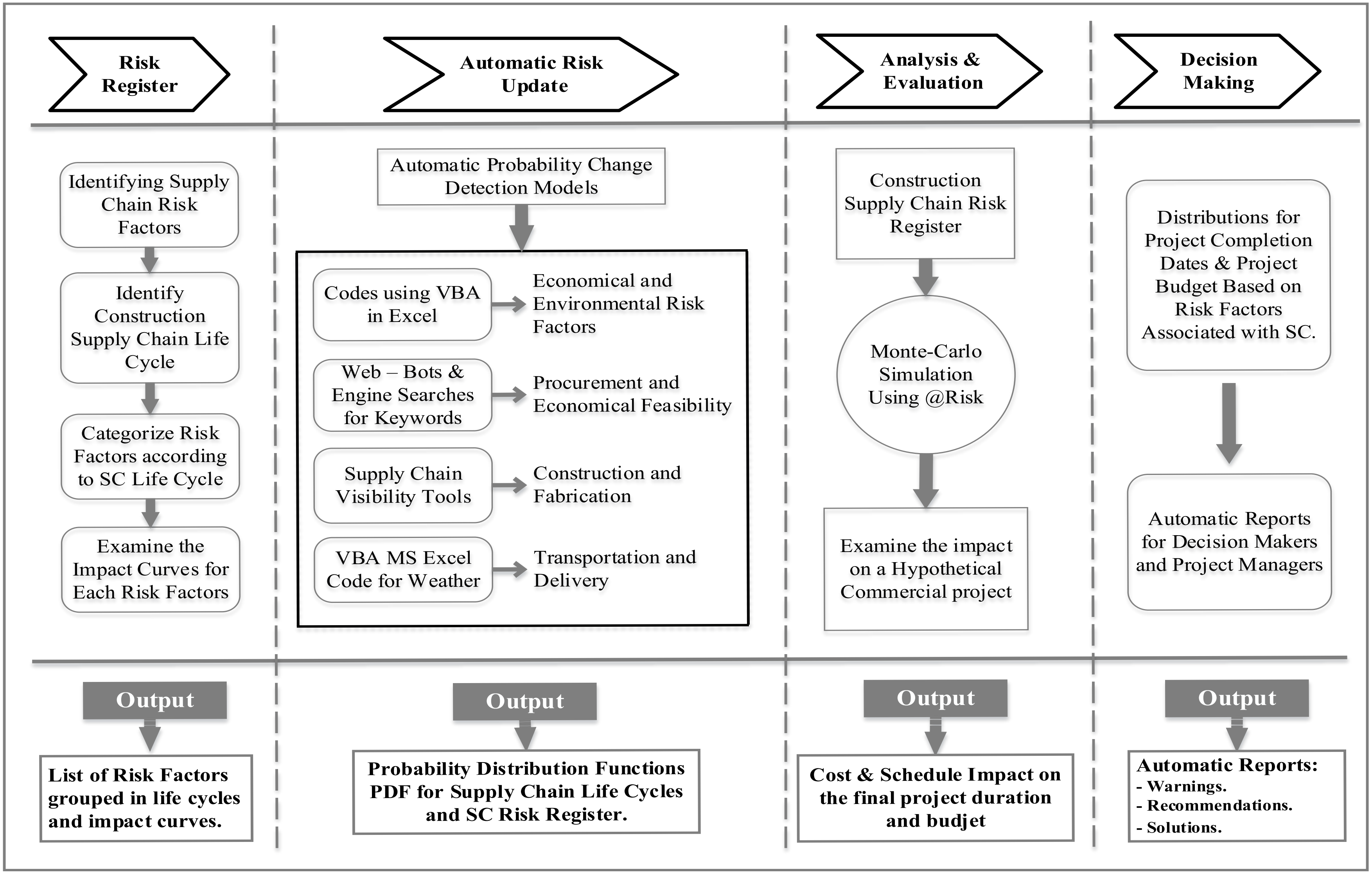


Figure 3.1: Components of the Framework

The first module is the risk register, which includes identification of the supply chain risk factors and the supply chain life cycle. It also includes risk factor categorization according to the supply chain life cycle. The second module relates to automatic risk updates, which includes possible automated detection models for probability changes for each risk category. The framework's third module is the analysis and evaluation of time and cost impacts, which will be done using Monte Carlo simulation. Lastly, the fourth module in the framework is the decision support mechanism, which generates automatic reports to help project managers better understand the supply chain risks in advance. Details of these modules are discussed in the following subsections.

3.2.1 Risk Register

The risk register phase of the framework is important in order to identify all the factors and values required for the analysis phase. It requires four steps, as follows:

Identifying supply chain life cycles. The first step in the risk register module was utilized to identify the life cycle of a supply chain, and Figure 3.2 shows the life cycle of a construction supply chain. The construction supply chain life cycle involves specification, design, procurement, construction, transportation, and site storage.

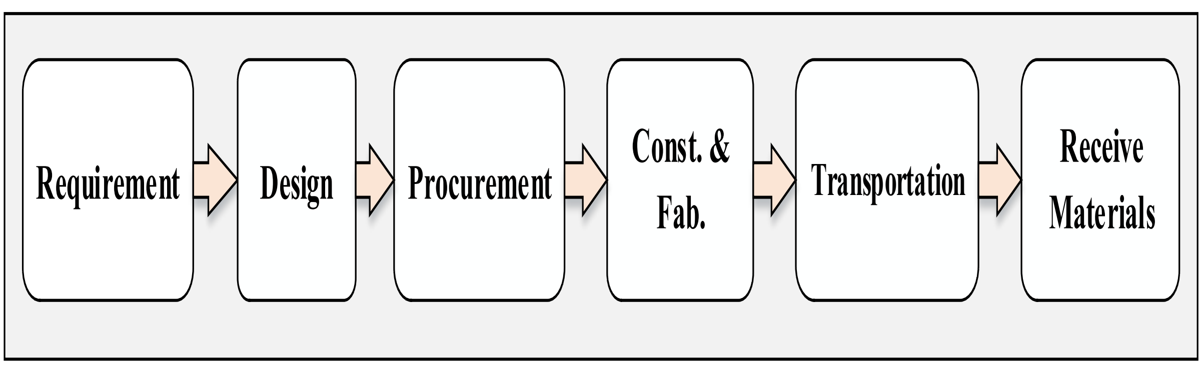


Figure 3.2: Construction Supply Chain Life Cycle

Identifying supply chain risk factors. An extensive study of the literature was performed in order to develop an initial list of supply chain risk factors. First, a list of 42 risk factors was identified as the key factors described in the supply chain literature. These factors are independent factors and have been considered in the study separately. Then, the list was reduced to the 25 risk factors that most influence construction supply chain, as shown in Table 3.1. These key factors are mostly quantitative and can be evaluated at different stages during construction. In addition, automating frequent updates of these factors is perceived to greatly improve supply chain management and their impacts on project time and cost. Some factors are hard to quantify and automate, and 17 risk factors were eliminated from the study, as shown in Table 3.2. Also, in many interviews with experts and practitioners, they agreed with the giving list being eliminated. Some of the 25 factors (e.g., weather change factors) are considered as uncertainty factors that affect activity duration, while others (e.g., environmental hazard factors) are considered as risk events that influence the whole project, as shown in Figure 3.3.

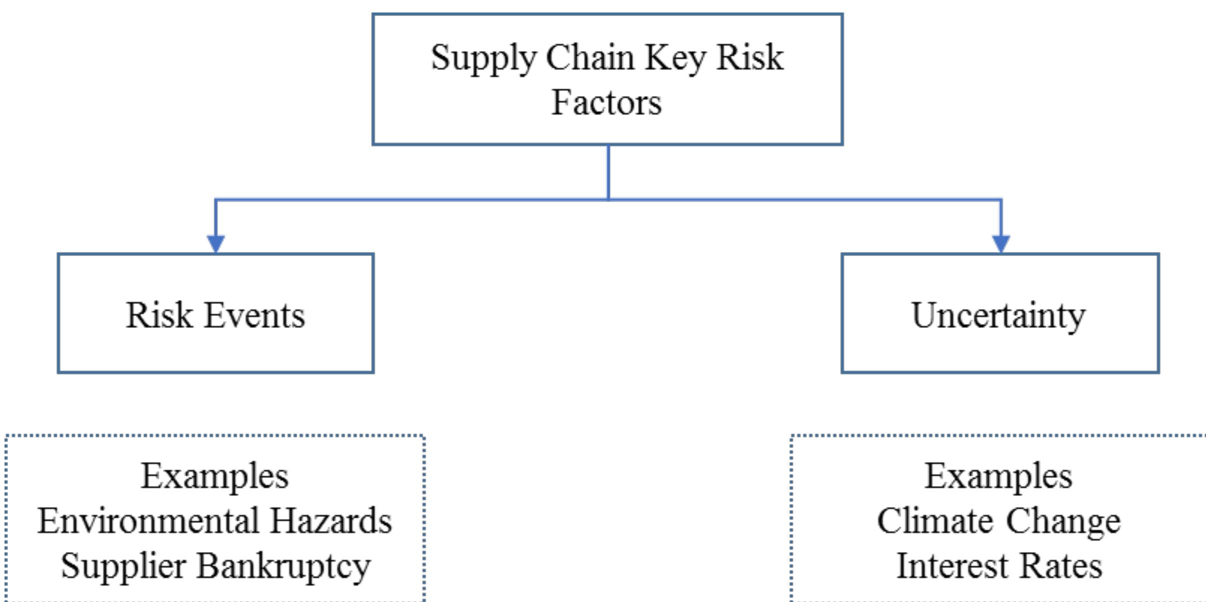


Figure 3.3: Types of Risk Factors Considered in the Research

Table 3.1: Construction SC Risk Factors Categorization According to Life Cycle

Construction Supply Chain Risk Factors	Construction Supply Chain Life Cycle					
	Requirement	Design	Procurement	Const. & Fab.	Transportation	Site Storage
Timely/correct input from clients	X					
Clarity of Requirements	X					
Achieving project milestones	X					
Permissions from regulators		X				
Timely/correct input from consultants		X				
Changes in specification		X				
Drawing approvals		X				
Timely and correct input from suppliers		X				
Price Change			X			
Subcontractor bankruptcy			X			
Market Condition (interest, exchange)			X			
Late client payment			X			
Early or late deliveries				X		
Speed of construction				X		
Bad performance from suppliers				X		
Insufficient Resources				X		
Insufficient Workspace				X		
Insufficient Equipment				X		
Weather Change (Precipitation, Temperature)					X	
Environmental Hazards					X	
Item Damages					X	
Delivery bottlenecks					X	
Site / storage space						X
Accessibility to Site						X
Timely Installation / testing						X

Categorizing risk factors according to supply chain life cycle. In this step, the key supply chain risk factors were categorized according to the life cycle, as shown in Table 3.1. The risk factors were grouped based on how significantly they influence each life cycle phase. Some risk factors could be grouped under multiple lifecycle phases; however, in this study each risk factor was taken only once according to its significance in the life cycle phase.

Table 3.2: Factors Hard to Automate and Quantify

No.	Risk Factor	No.	Risk Factor
1	Fragmented decision-making	10	Quality/excessive snagging
2	Appropriate design for scheme	11	Site impact on local community
3	Issues not for in planning	12	Competency of site mgmt.
4	Volatility of SC workflow	13	Effectiveness of arrangements
5	New technology or technique	14	Consistency of suppliers
6	Shared objectives	15	Scheme viability long term
7	Design too rigid for change	16	Experience of subcontractors
8	Competency of project team	17	Security
9	Responsiveness of suppliers		

Examining the impact of each risk factor. In this step, each risk factor was studied in detail using information from the literature in order to obtain an accurate impact assessment for each phase. An impact curve for each supply chain risk factor is the output of this step of the framework. An example of the impact of temperature and precipitation on achieving changes in productivity obtained from a study by Li et al. (2013) on risk assessment and impacts is shown in Figure 3.4. The impact curves were utilized to develop the supply chain risk register needed for the analysis and evaluation module. The temperature and precipitation impact data are available in Appendix A.

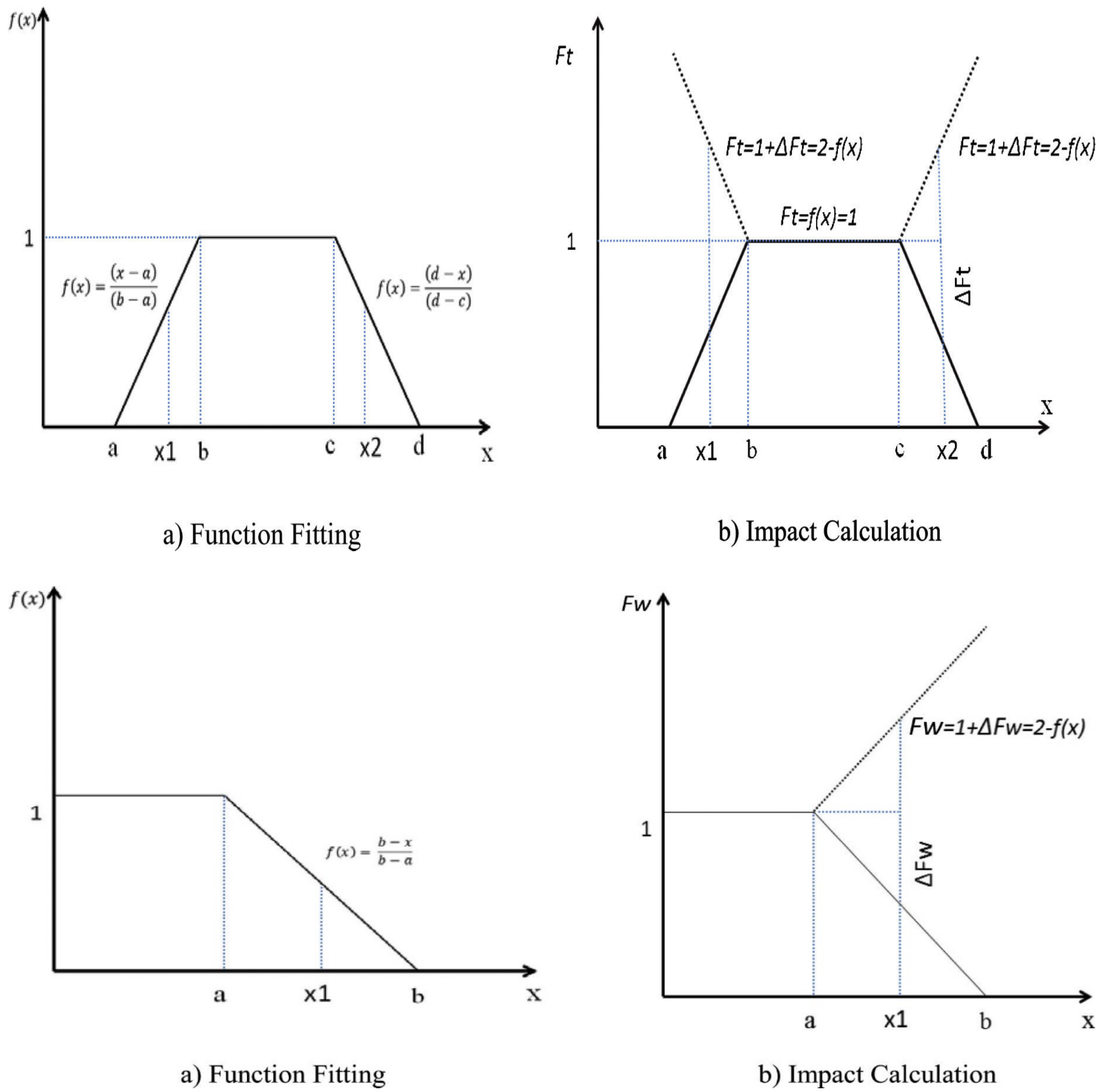


Figure 3.4: Impact Calculation for Temperature and Precipitation, from Li et al. (2013)

3.2.2 Automated Risk Updates during Construction

The second module of the framework, shown in Figure 3.1, is the "Automatic Risk Update". In this module, detection the default probability distribution for each risk factor. In this phase, data are collected automatically and continuously during the project life cycle. Table 3.3 shows the proposed models for automatically collecting the required data.

Table 3.3: Proposed Detection Models for Probability Change

	CSC Life Cycle	Proposed Probability Detection Model (s)
1	Requirements	Cloud Networks & compatibility with the existing systems
2	Design	Database / Online tools
3	Procurement	Exchange Rates from web / Price Trends Keywords for suppliers.
4	Construction	SC Visibility and comparison against schedule
5	Transportation	Historical and Weather Forecast from web Keywords for Hazards.
6	Receive Materials	GIS and RFID tags for tracking & visibility Wireless RFID Systems

For each life cycle in the project's supply chain, there will be several models intended to collect data from their sources and then obtain probability values or distributions accordingly. For example, for the transportation phase, this study built a model to collect weather data from the web. Historical weather data were used as a benchmark for obtaining the default probabilities. Then, the weather forecast data were used to update the default probabilities to current probabilities. This weather data model was developed using Visual Basic Applications (VBA) in MS Excel to automatically export the data from their source to Excel tables. Using VBA in Excel is proven in the study to work with weather models. This approach, however, might not work for calculating data related to other risk factors, and thus other data collection methods will be used, as shown in Table 3.3.

The outcome of the automatic risk update module will include six different probability detection models for a construction supply chain life cycle. Each model will be designed in order to automatically detect, quantify, and update probability curves. These curves are utilized in the supply chain risk register, and the developed risk register will be obtained for the analysis of time and cost impacts. Figure 3.5 shows the six different models that feed the SC risk register.

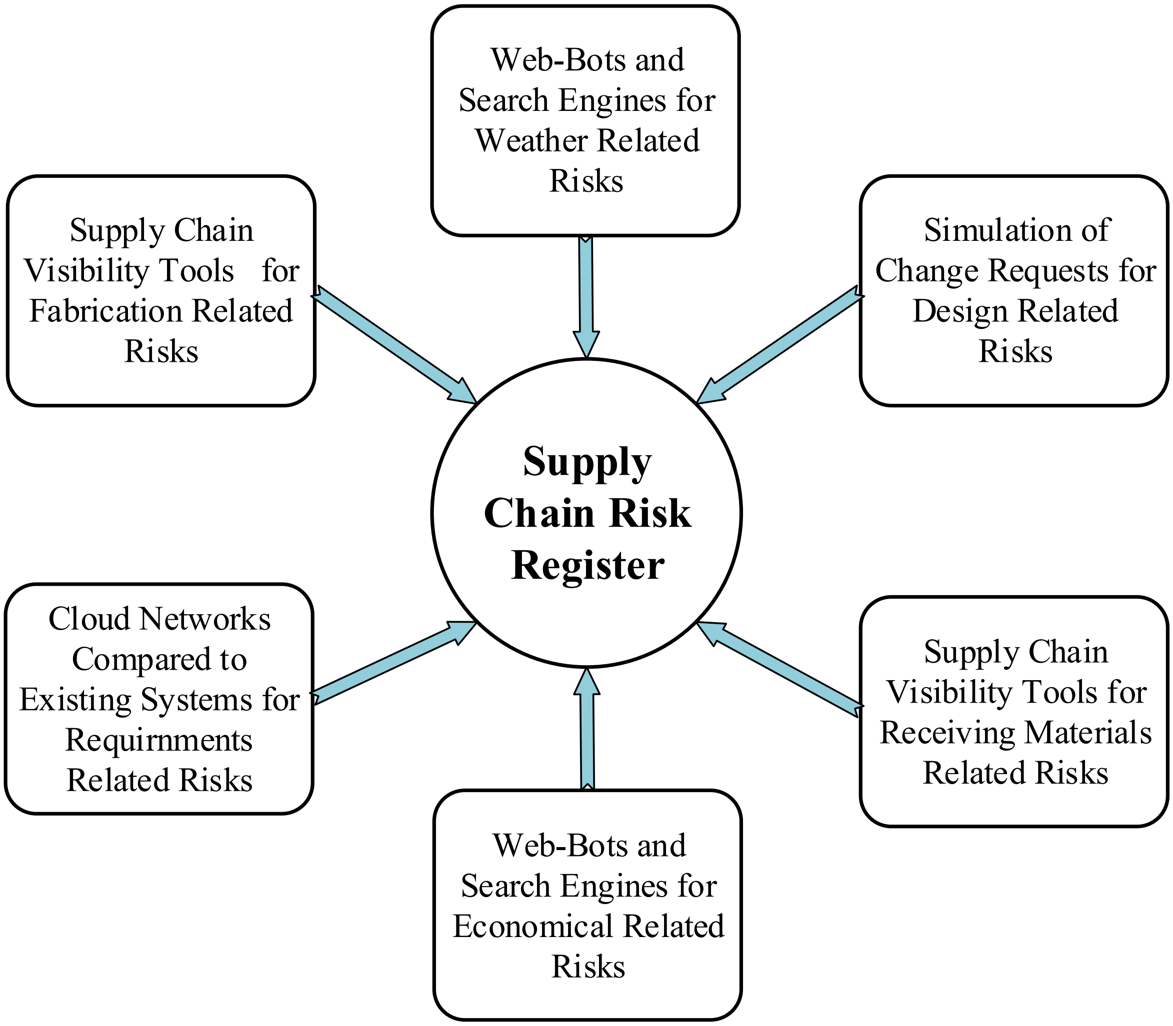


Figure 3.5: Automatic Detection Models to Feed the SC Risk Register

The six detection models shown in Figure 3.3 will be integrated into the supply chain risk register. According to Figure 3.6, the analysis is applied on the key supply chain activities in two stages. The first stage happens before the start of the project using the default probabilities of the identified risk factors for calculating the initial risk values. Afterwards, during the project execution, the automatic detection models are used in order to update the probabilities of the risk factors and then update them accordingly. Figure 3.6 shows the impact of these automatic detection models on project duration.

3.2.3 Analysis and Evaluation

As will be discussed in detail in Chapter 4, the analysis and evaluation module was designed according to the workflow explained in Figure 3.7. This module requires three inputs: (1) a list of risk factors for each lifecycle phase; (2) probability distribution curves; and (3) impacts for each lifecycle. These three inputs will form the risk register required for the analysis. Then, a Monte Carlo simulation approach was applied to investigate the impact of these risks on a given project's time and cost. An industrial project was studied to determine the impact of supply chain-related risks on the project. The output of the analysis and evaluation module was the probability distribution functions for project time and cost. These distributions will be automatically and continuously updated in order to support contractors and project managers assess the unseen factors related to their projects.

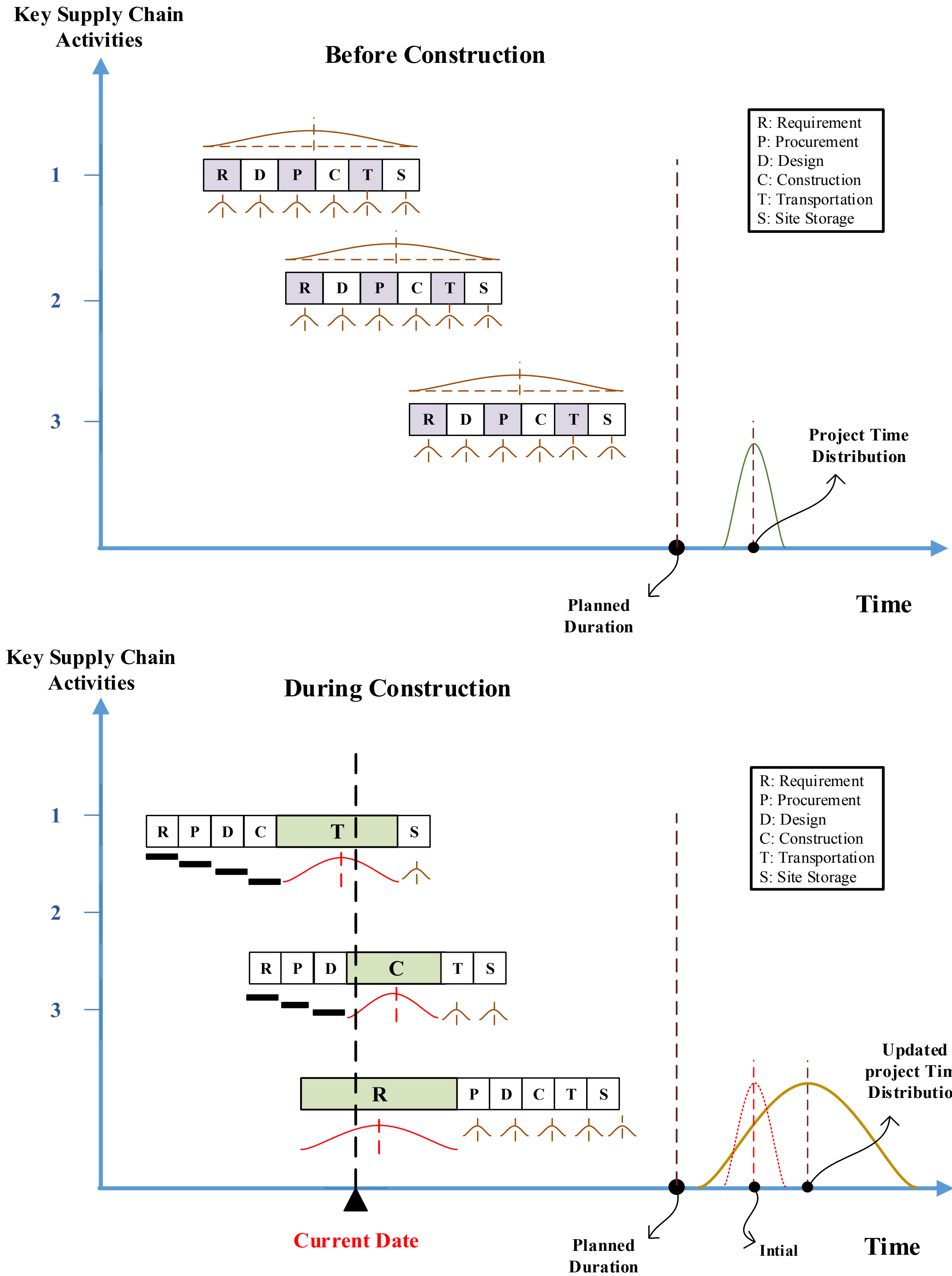


Figure 3.6: Updating Risk Probabilities for CSC Key Activities

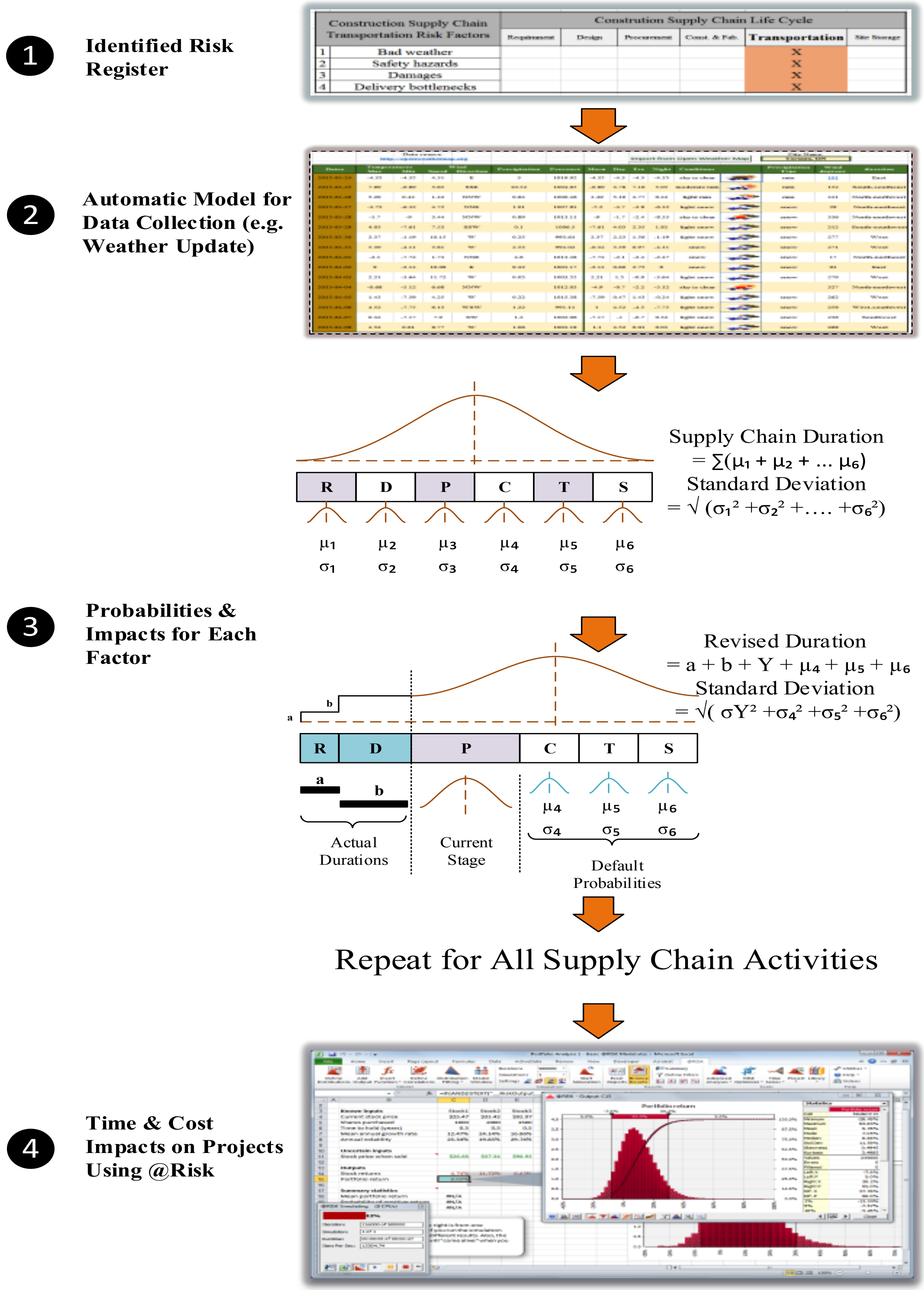


Figure 3.7: Workflow of the Risk Update and Impact Assessment

3.2.4 Decision Support

The last module of the research framework, shown in Figure 3.1, is "Decision-Making". This phase involves automatic reports and updates for project managers and decision-makers with the following:

a. Progress updates

b. Warnings

c. Source of problem (if any)

d. Cost and schedule impact on the project

The continuous updated reports will help decision-makers recognize the risks associated with their projects and allow them to take early decisions and actions to manage those risks.

3.3 Conclusion

This chapter presented the proposed framework for the automatic detection of probability changes along with its conceptual approach. The framework consists of four main steps, and each one was explained in detail. In the next chapter, an intelligent supply chain visibility model for materials tracking will be presented with a case study in order to show the effectiveness of the model.

Chapter 4: Supply Chain Visibility Tools for Tracking and Assessing Supply Chain Risk Changes

4.1 Introduction

In this chapter, an intelligent framework for supply chain visibility will be introduced in detail. The chapter will begin with presenting the importance of supply chain visibility for risk management, followed by a real-life industrial project case study, which entails the supply, erection, operation, and maintenance of a gas turbine at a power and desalination plant. Then, the pipe spool manufacturing and transportation process will be presented. The analysis in this chapter will follow the framework explained in Chapter 3 in order to study the impact of the construction-related SC risk factors on the project. A sensitivity analysis of the different scenarios is also presented in order to show the importance of using SCV tools in risk management. Finally, a discussion and conclusion are presented at the end of the chapter.

4.2 Supply Chain Visibility for Risk Management

As discussed in Chapter 2, a common problem in construction planning, especially in large industrial projects, is materials management, which is affected by situations such as lack of required materials, poor storage of critical equipment, improperly sequenced delivery of materials, and overall process inefficiency. One of the main challenges facing construction managers is keeping track of all actions taking place on site in order to detect potential problems and to select appropriate corrective actions. The additional costs incurred by a project to manage and maintain the early arrival of the materials is huge. On the other hand, the late arrival of materials often leads to extensive delays that cause substantial overruns, thereby shrinking or eliminating project profit margins.

The many risk factors that influence the progress of the supply chain become problematic when the probability of occurrence of these factors and their impacts are not well-defined. These factors often arise out of a lack of supply chain visibility, and in order to track supply chain progress, several techniques have been used, including radio frequency identification (RFID), global positioning systems (GPS), bar coding, and machine sensors. Automated tracking of materials on construction projects using these technologies has the potential to greatly improve project performance.

This research introduces an intelligent framework for supply chain visibility and applies it to pipe spool manufacturing processes. The proposed framework has been designed to enhance risk management by helping decision-makers promptly recognize the probability of the occurrence of risk factors throughout the supply chain life cycle. Using a hypothetical case study for pipe spool production, various risk factors are simulated with the @Risk software. The results indicate that the efficient dynamic tracking of risk events increases supply chain visibility and leads to better assessments of deviations in construction time and cost.

4.3 Case Study

To demonstrate the practicality of the proposed framework and to calibrate its functions, a hypothetical project for pipe spool production has been used. The project entails the supply, erection, operation, and maintenance of a gas turbine at a power and desalination plant. This megaproject includes a number of milestones and key activities and is a fast-track project. The focus of this study is on the key activities that require the study of SC risk management, particularly pipe spool items. These activities are essential for the project and have a significant role in its completion. Process piping was chosen for illustration as it is a common element of most industrial construction projects and is known to suffer from the effects of uncertainty in the supply network. The pipe spool manufacturing and transportation process is illustrated in Figure 4.1.

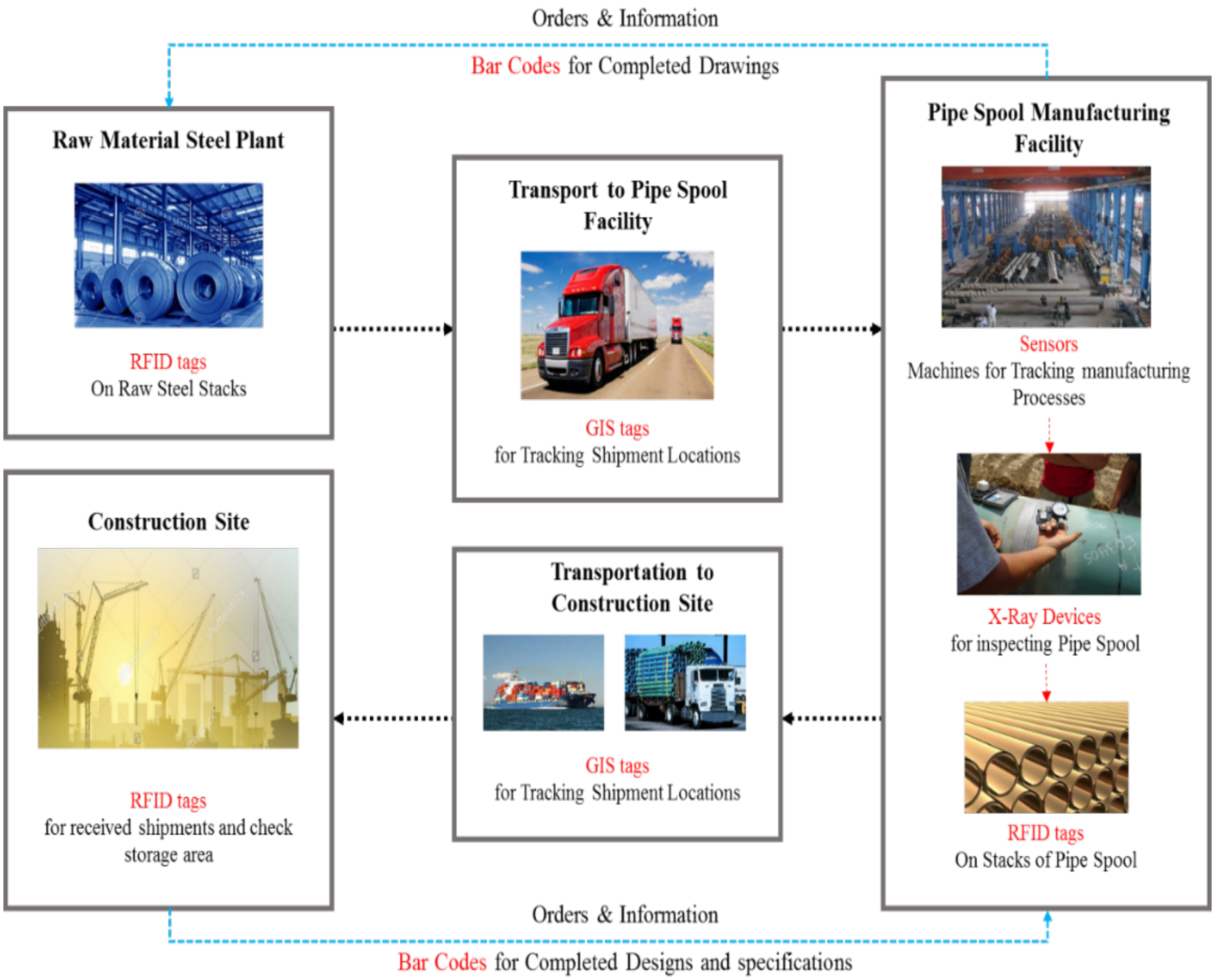


Figure 3.8: The Pipe Spool Process for the Proposed Model

The study involves 20 pipe spool activities at different stages in their SC life cycles. The analysis in this research compares three supply chain monitoring methods: (1) No SC updates; (2) Typical manual periodic updates; and (3) Supply chain visibility tools. The main factors related to the construction and fabrication phase are shown in Table 1. A detailed risk register was then defined, including individual probability distributions for risk factors and expected impacts. An initial MC simulation was run with 5,000 scenarios, and the experiment was repeated 10 times. The results produced a project duration distribution that ranges between 641 days and 675 days (as opposed to the 620-day deterministic duration without considering risk), as shown in Figure 5.

Table 3.4: Pipe Spool Manufacturing and Transportation Process

	Pipe Spool SC Model	**Automatic Detection Method**
1	General Project Specification	Scan bar code for completed documents
	Design Pipe Spools	
2	Standard Pipes	Scan bar code for completed design
3	Custom Made Pipes	Scan bar code for completed design
	Fabricate Pipe Spools	
4	Spools production	Monitoring roller machine using sensors
5	Spools transportation to the making facility	GIS tags for packages for completed packages
6	Spool unwinding	Monitoring unwinding machine using sensors
7	Un-welded pipe production	Monitoring rollers using sensors
8	Pipe welding	Monitoring high-pressure rollers using sensors
9	Pipe cutting	Monitoring cutting machines using sensors
10	Seamless pipe production	Monitoring cutting machine using sensors
11	Seamless pipe treatment	Monitoring treatment process machine
12	Inspection Pipe Spools	X-ray gages for inspection
13	Stacking Pipe Spools	Apply RFID tags on stacks
14	Transportation to construction project	Apply GIS tags for shipments
15	Receive Pipe Spool stacks.	Scan RFID tags for stacks onsite

4.4 SC Visibility Framework

To support efficient supply chain management, this study proposes a supply chain visibility framework, which includes three main functions: (1) identification of possible SC-related risks; (2) automatic detection and updating of the probabilities associated with risk factors; and (3) performing sensitivity analysis and generating reports for decision-makers. Figure 4.2 shows a schematic of the proposed framework as related to supply chain visibility, and incorporates the automatic detection tools.

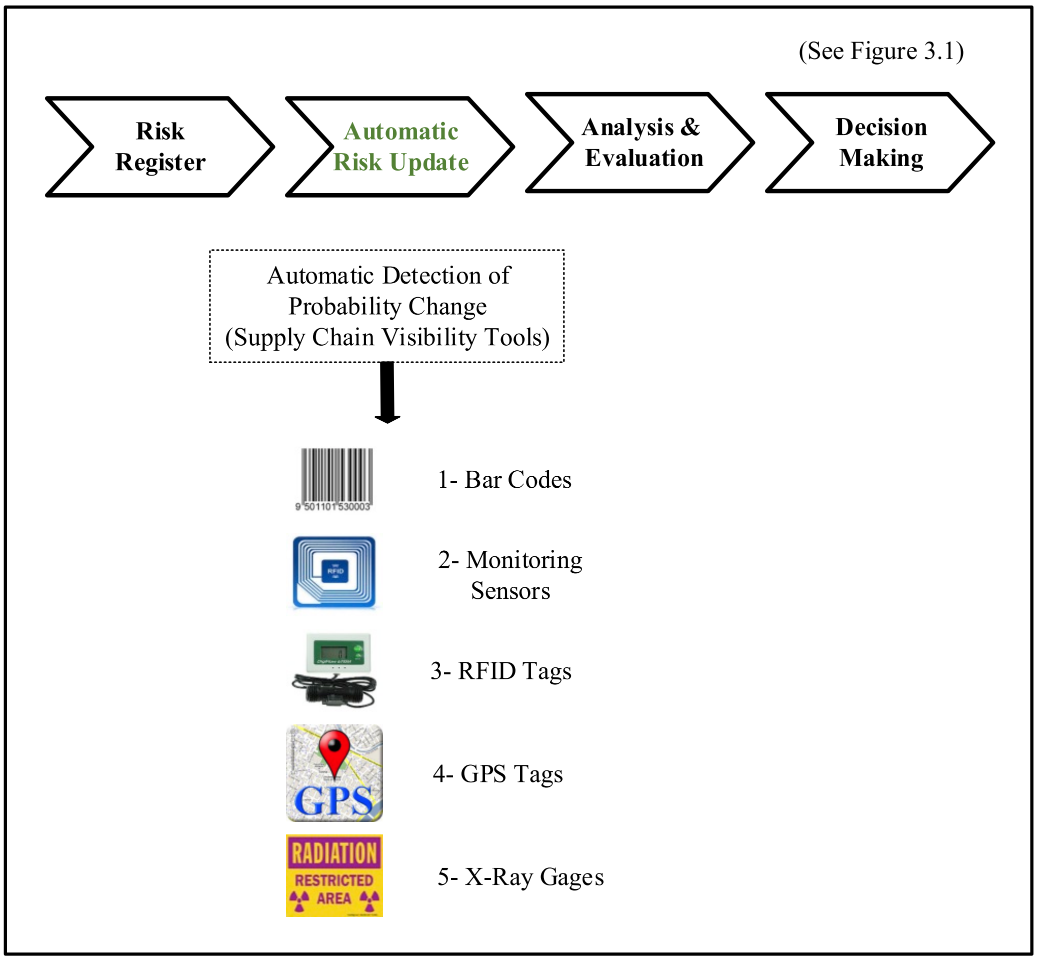


Figure 3.9: Details of the Supply Chain Visibility Step of the Proposed Framework

4.4.1 Risk Register

As discussed in Section 3.2, this component relates to the project activities that require supply chain management (e.g., pipe spool manufacturing). For each activity, the full supply chain lifecycle is analyzed, which involves the following phases: S-specification; D-design; P-procurement; C-construction; T-transportation; and R-receive materials. An extensive study of the literature was conducted in order to develop an initial list of key SC risk factors that relate to all SC phases. This list was then filtered based on expert opinion to retain only the top factors that influence each supply chain phase. As a result of these procedures, a detailed risk register is developed, involving three types of data:

1. List of risk factors for each lifecycle phase: these key risk factors are quantitative and thus can be evaluated at different stages during construction. Automating the frequent updating of these factors is perceived as a means of greatly improving SC visibility.
2. Probability distribution curves: each risk factor is assigned a probability distribution curve that represents its default level of uncertainty.
3. Impact on each lifecycle phase: different models are utilized to quantify and store the impact of each risk factor on the activities' durations.

4.4.2 Supply Chain Visibility Detection Tools for Data Collection

This component uses various tools for the automatic collection of data that can update the risk factors. These tools include RFID tags, machine sensors, bar codes,; X- Ray devices, and GPS tags.

RFID tags, machine sensors, and bar codes. Putting RFID tags on stacks means that information is available about the number of units ready for shipping at a specific time. Two types of data collected from these devices are known as n and ti, where n denotes the number of units and ti represents an individual time for each unit. For example, consider an order for 100 stacks of steel sheets that need to be shipped together and that the time required for preparing the stacks is 10 days (10 stacks per day). Using RFID tags, for example, provides up-to-date progress percentage for the stacks. Figure 4.3 reflects the importance of using RFID tags for tracking the progress of a specific order. In the formulation of the delay a specific order, it is assumed that the productivity rate in the production process is a constant value (i.e., the productivity rate does not vary over time).

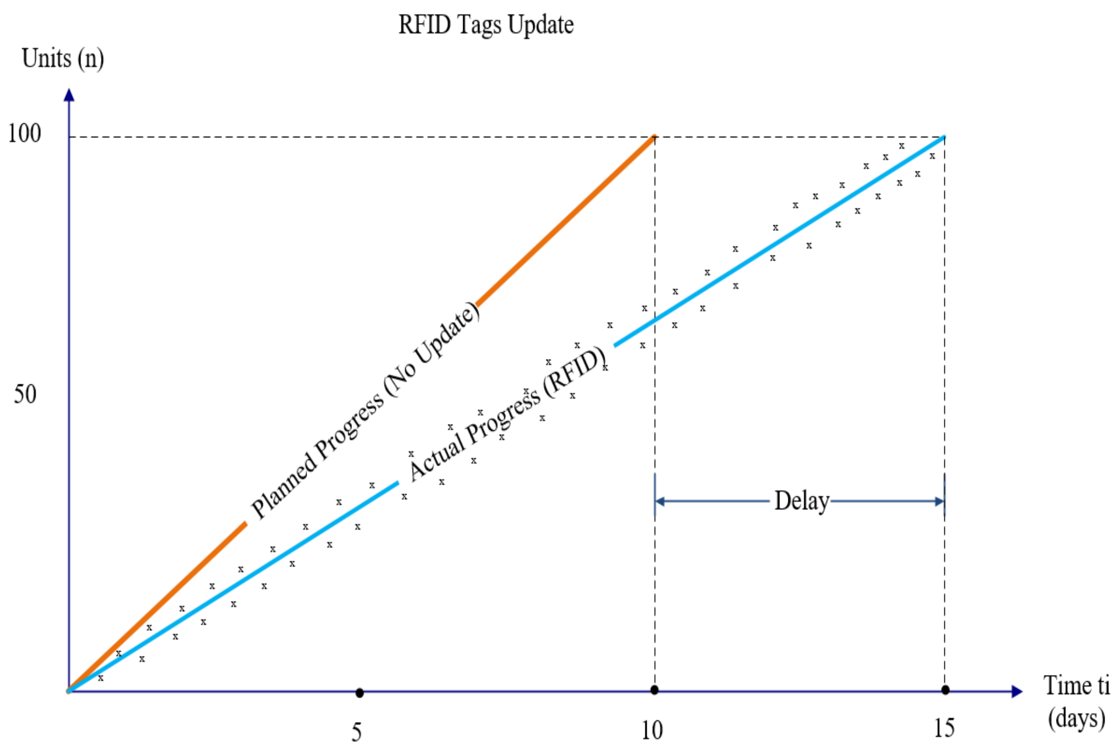


Figure 3.10: Actual Progress of Tracking an Order Using RFID Tags

Accordingly, it is possible to estimate the expected delay for a specific order as a percentage by using Equation 1, as follows:

$$\% \text{ Delay for a specific order } = \frac{\frac{N}{P} - D}{D} * 100 \quad (1)$$

where N is the total number of units, D is the planned duration for completing all units, and P is the actual progress rate determined from automated RFID readings. The same approach can be used when collecting data with sensors and bar codes. The more data obtained, the more accurate the delay percentage estimation will be, and earlier delay recognition will help with better mitigating the risk of insufficient materials and resources.

X-Ray Devices. Using X-Ray devices helps to track the quality of the produced items, and at the same time helps with production progress. It identifies which items have passed the specification test, and based on this identifies the quantity of these units. For each automatic update, the system receives the number of units passing or failing an inspection at a specific time. Accordingly, the percentage of the delay can be calculated using Equation 1, while the failure rate can be calculated using Equation (2), as follows:

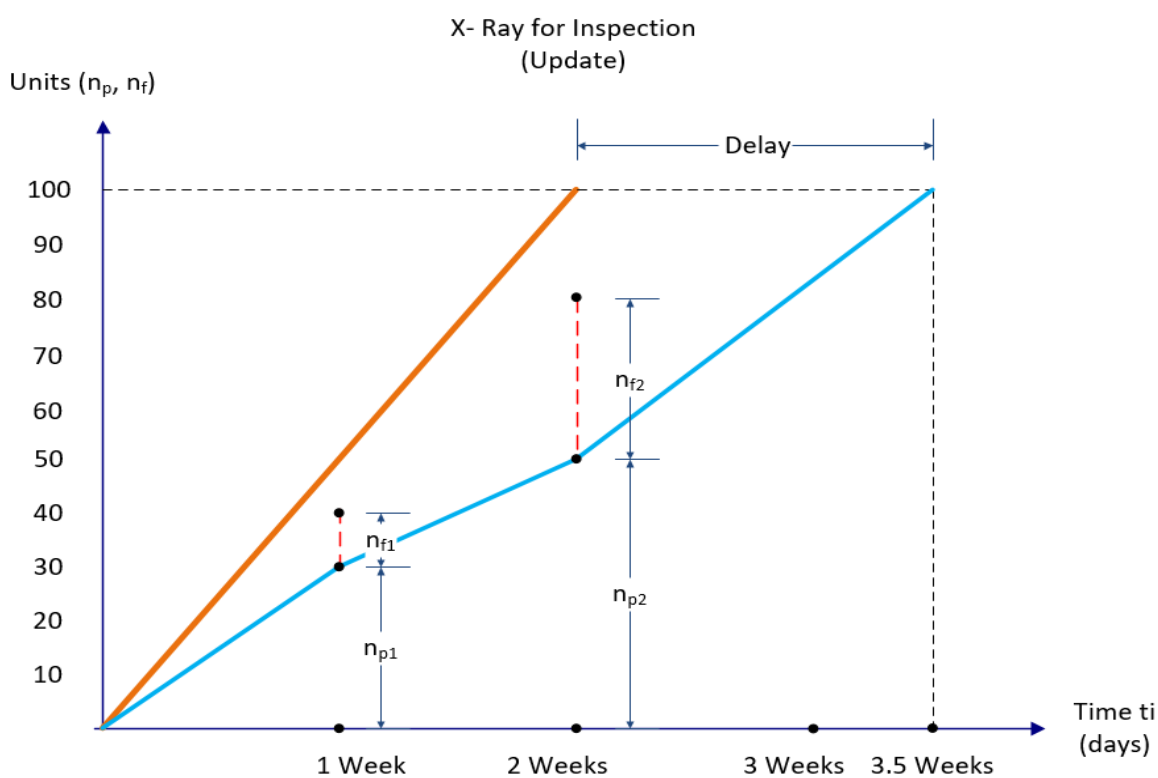


Figure 3.11: Graph for X-Ray for Inspection

GPS tags. GPS tags will be assigned to specific shipments; for example, when an order for a hundred-pipe spool needs to be shipped, one GPS tag can be assigned to the whole shipment. Assuming that the shipment will be transported by ship, the distance is 900 km, and the average speed of the ship is 30 km per hour, therefore the planned duration is 30 hours. The actual progress achieved is based on information from GPS devices. GPS can help with lost items as well, and can be used for validating the transportation and environmental risk detection models.

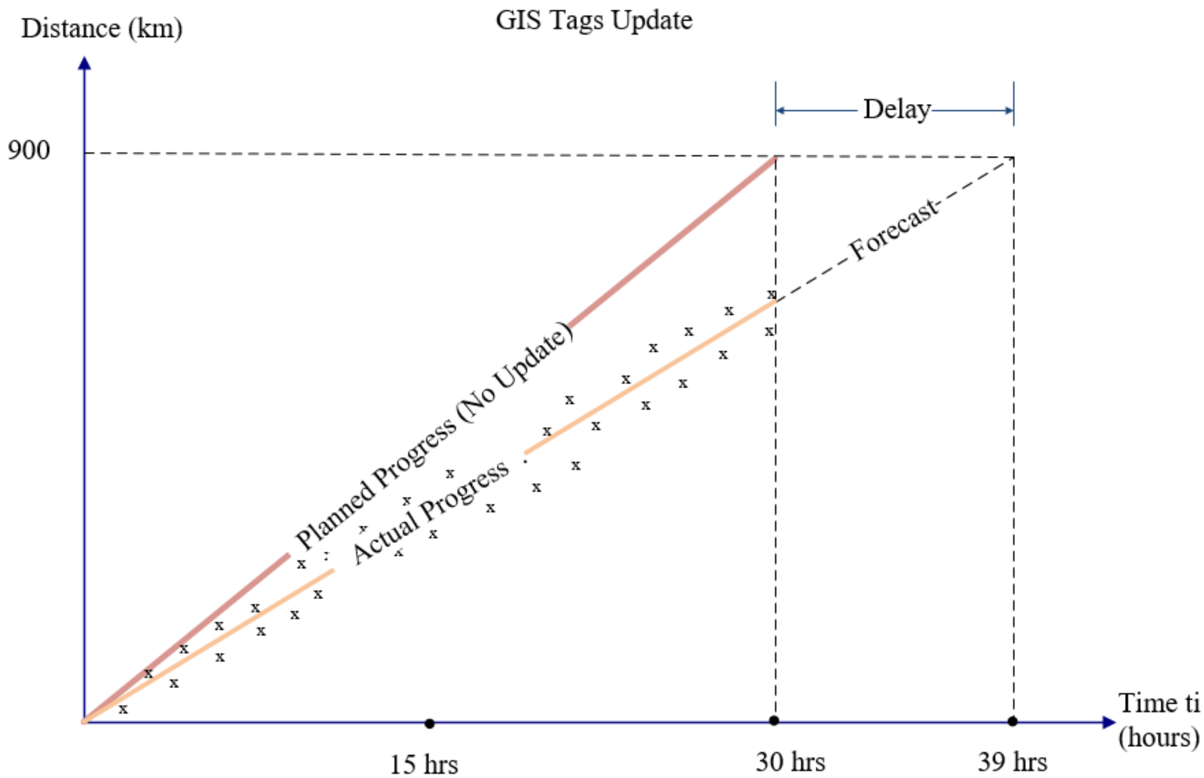


Figure 3.12: Graph for GIS Tags Update

4.4.3 Analysis and Simulation

As discussed in Section 3.3, the third component of the proposed framework is analysis and simulation. With the project risk register defined, a Monte Carlo simulation (as shown in Figure 4.6) is applied to quantify the impact on the project's time and cost, and the outputs of the simulation are probability distribution functions for the project's time and cost. Before the project starts, the simulation produces default project time and cost probability functions. As the project progresses and the SC visibility tools collects automatic updates about the risk factors, the individual probabilities are adjusted and the simulation is rerun to produce modified probability distribution functions.

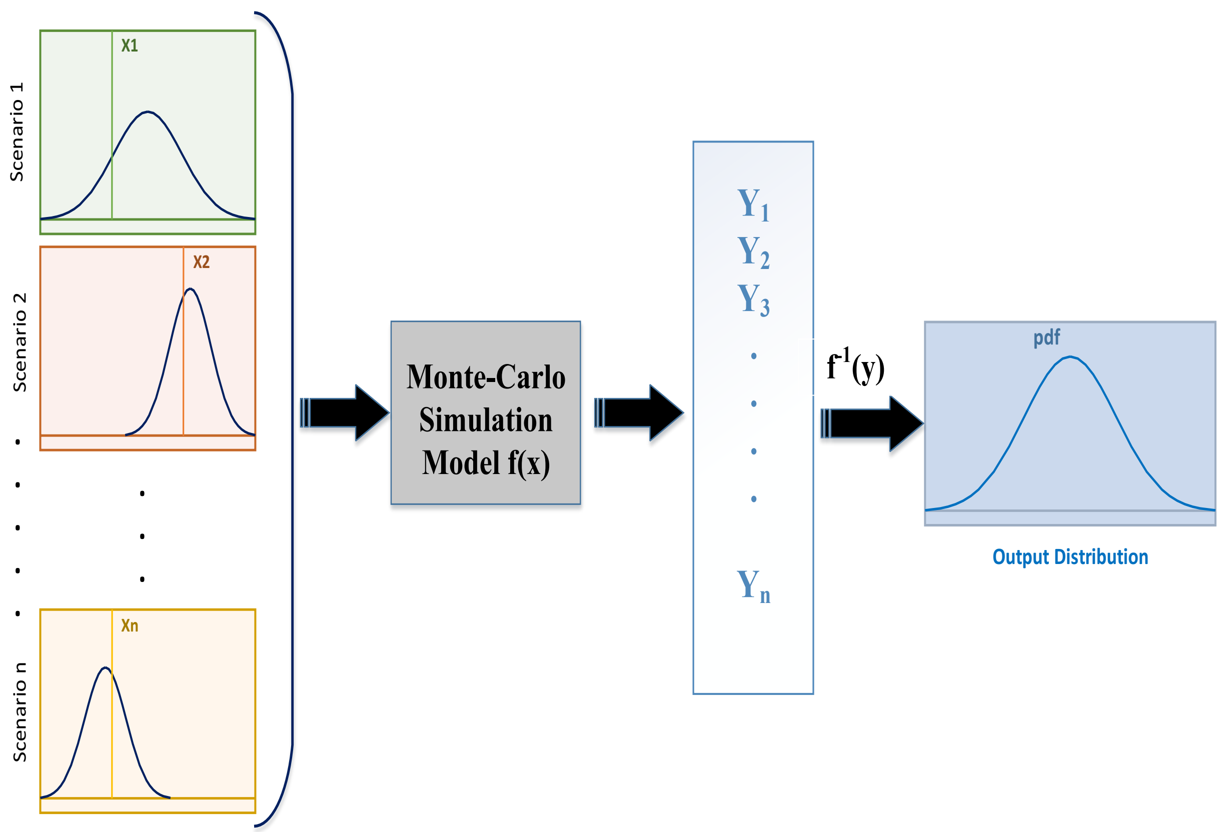


Figure 3.13: Monte Carlo Simulation Approach

These distributions are automatically updated to support decision-makers in their assessment of unforeseen factors related to their projects. To carry out the simulation, a commercial tool, @Risk, has been used and customized to interactively allow new updated information about risks to be considered at different project update points.

4.4.4 Project Time and Cost Update

In this component, an automated and iterative risk update process is carried out to monitor all supply chain activities (which experience different life cycle phases) using various SC visibility tools, and accordingly update the project time and cost distributions, as shown in Figure 4.7. In this figure, it is assumed that a project includes 5 pipe spool activities that require supply chain management along two project update times. Given that a detailed risk register is defined for all the activities, the analysis starts by performing a Monte Carlo simulation using the default probabilities stored in the register. The project time distribution in this case is shown at the bottom, which exhibits a reasonable narrow range of project duration changes.

Before the project starts, at the first project update, the first activity experiences risk factors related to the transportation phase of the related items that are shipped by sea (as determined by a SC visibility tool such as extreme weather information). Accordingly, the distribution of Activity 1's transportation time is adjusted by multiplying its original distribution by the delay percentage calculated from Equation 1. Based on the individual probability distribution modifications in project update 1, the Monte Carlo simulation is re-run, and accordingly, a new revised distribution function for the project duration is developed, as shown in Figure 4.7.

The same process is followed for the second project update, resulting in a third revised distribution for the project duration. The above process not only automates the tracking of risks, but is also capable of producing reports that better portray the project duration distribution. These reports provide decision-makers with information about the effects of unforeseen risk factors and their impact on the project's cost and schedule. The main reason for using a Monte Carlo simulation in construction projects is to evaluate the enormous amount of calculations related to thousands of scenarios that consider many combinations of risk effects.

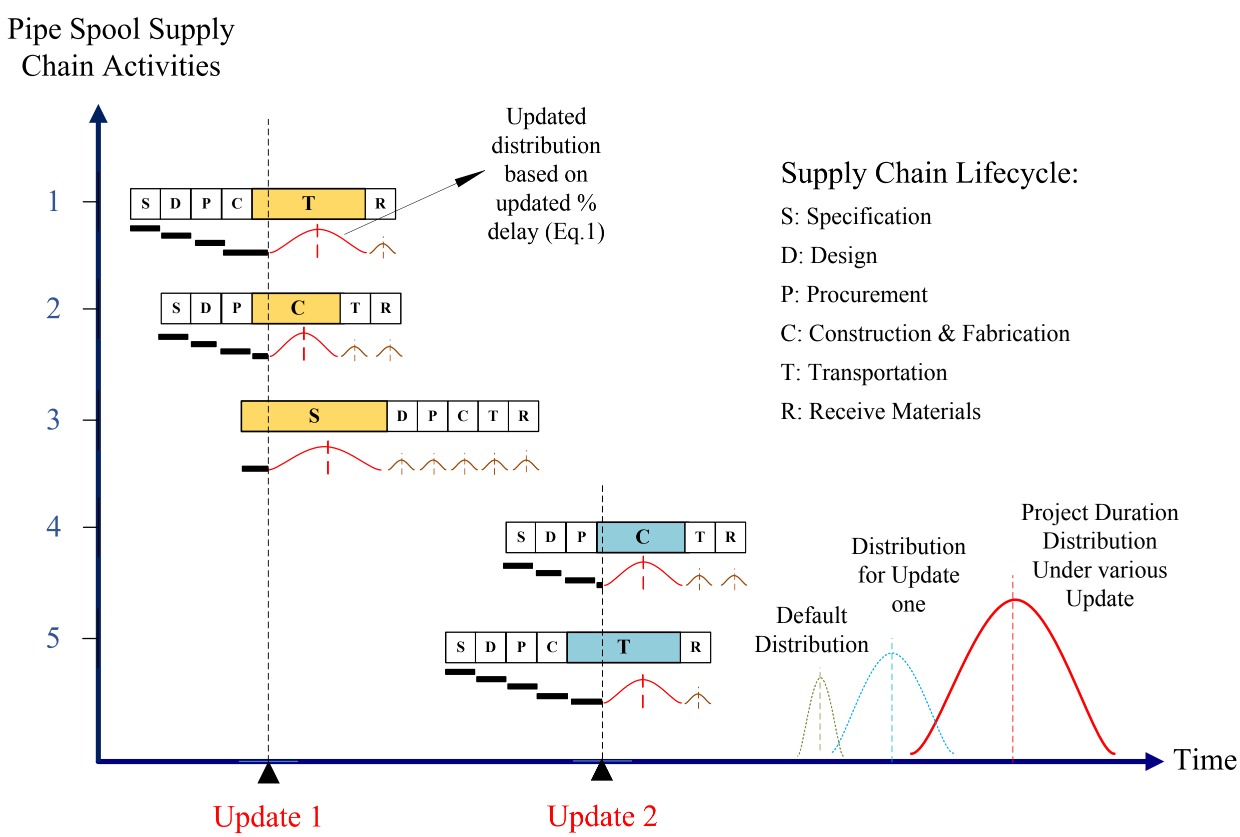


Figure 3.14: Risk Probabilities for Pipe Spool Activities

4.5 Time and Cost Impacts (Visibility vs. No Visibility)

The deterministic project duration is 641 days. The pipe-spool-related activity duration is 471 days. Following the above step, frequent risk updates were performed, the MC simulation was rerun, and the project duration distribution was updated. Figure 4.8 shows how the project's duration became probabilistic after assigning default delay distributions for the pipe spool activities, which were gathered automatically using SCV tools. Different distributions represent this variation between 640 days and 672 days.

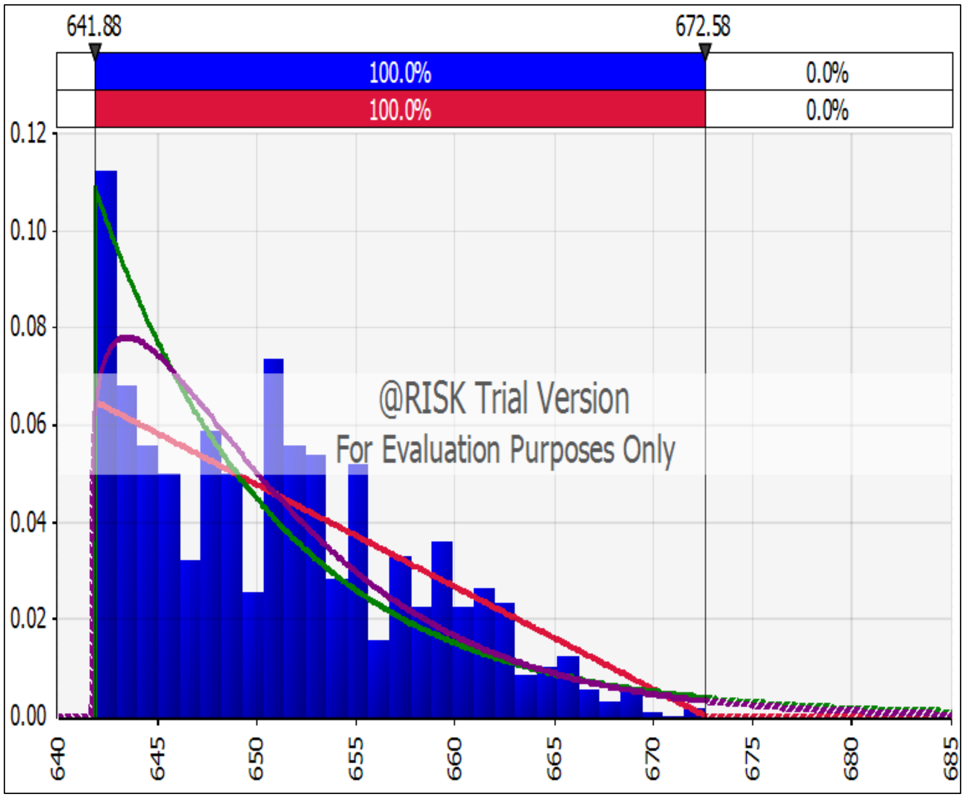


Figure 3.15: Variations in Project Duration

The required pipe spool activities' duration is 471 days. Based on the data collected from the SCV tools and after running the MC simulation, the procurement phase completion time distribution was updated. Figure 4.9 shows how the procurement phase duration became probabilistic. The results show that the best-fit distribution is a triangle distribution with a minimum value of 435 days and a maximum value of 505 days. .

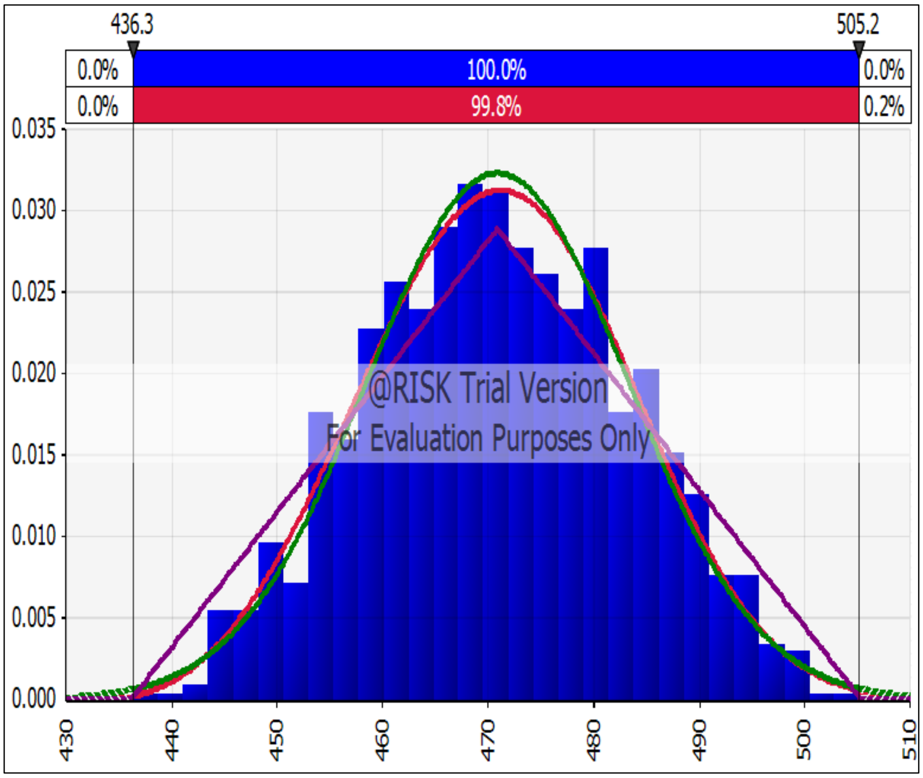


Figure 3.16: Variation of the Procurement Phase

4.6 Visibility vs. No Visibility

Following the above step, frequent risk updates were performed, the MC simulation was rerun, and the project duration distribution was updated. The comparison among the three methods of supply chain monitoring is shown in Figure 4.10. The first curve, on the left, represents the case when using no supply chain monitoring tools where the project duration is underestimated and the project time distribution is the initial MC simulation results. For this curve, no updates were carried out, and the distribution is narrow. The second (middle) curve represents the updated progress based on periodic manual reports. After receiving a specific report, the progress is updated and the completion time is forecast based on the new information. Since a modest type of update is used (usually late, as per the time of receiving monthly reports), the project duration distribution is wider. The third curve represents the use of frequently updated SC data (various individual points that relate to each individual pipe). Accordingly, the MC simulation results show the widest project time distribution, since actual progress shows delays and variability. This case study demonstrates that having the ability to track the actual productivity of any given item will provide better forecasting of project time variability.

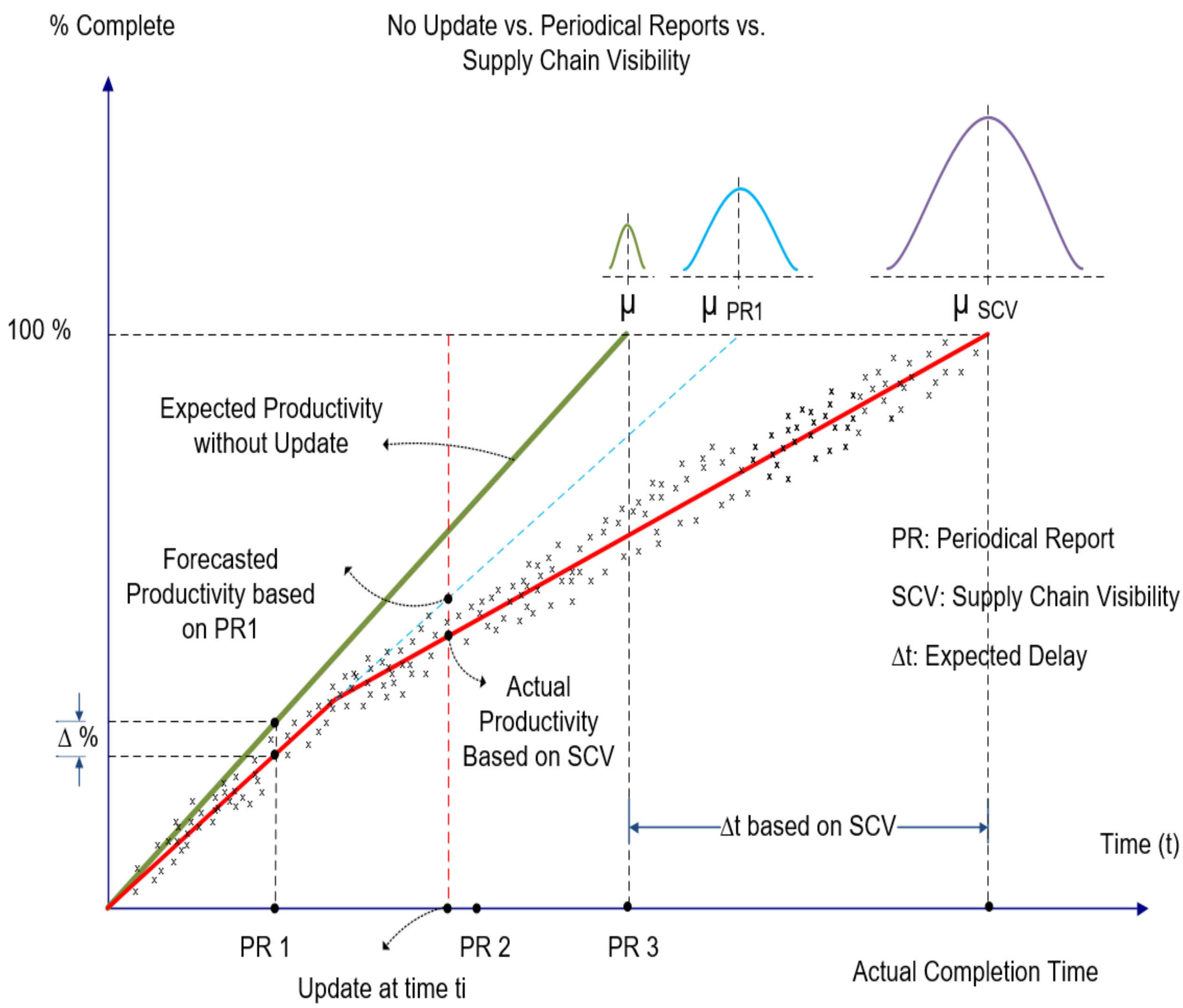


Figure 3.17: Comparison of the Level of Available Data and Their Impact on the Project

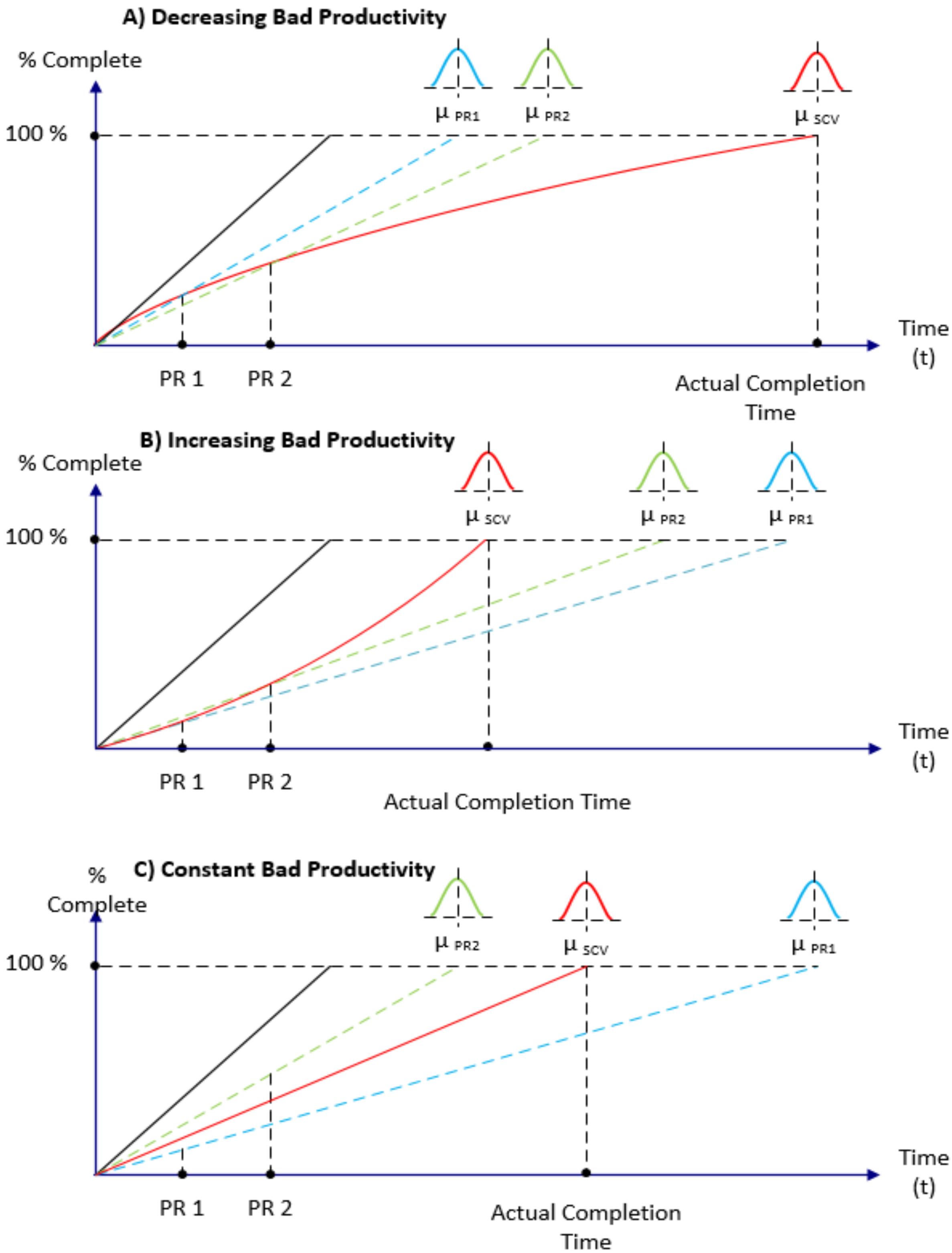


Figure 3.18: Comparison of the Level of Data Acquisition

4.7 Sensitivity Analysis

Results for Update 1 (Case 1). Figure 4.12 represents the variation of the total project duration due to the major factors explained earlier in Section 4.4, while Figure 4.13 shows the variation in the procurement phase only.

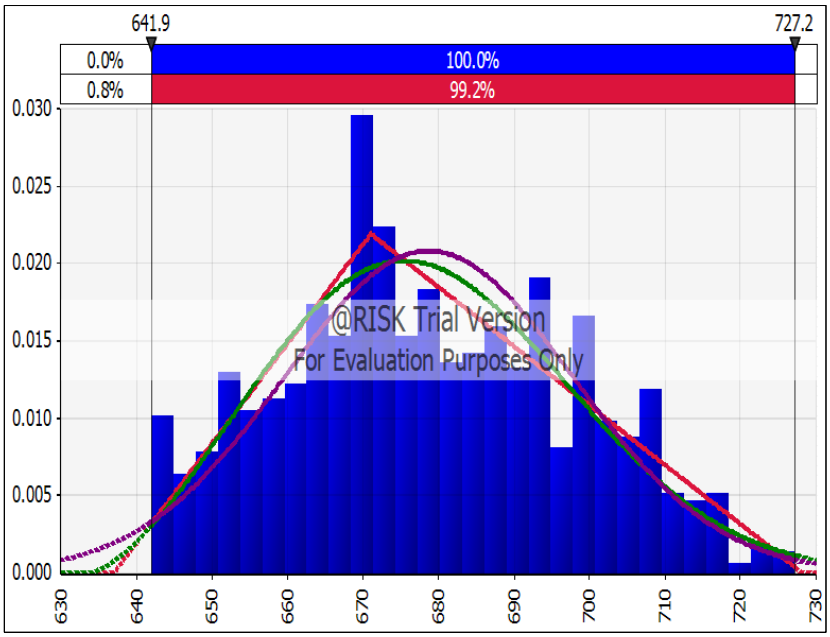


Figure 3.19: Variation in the Procurement Phase

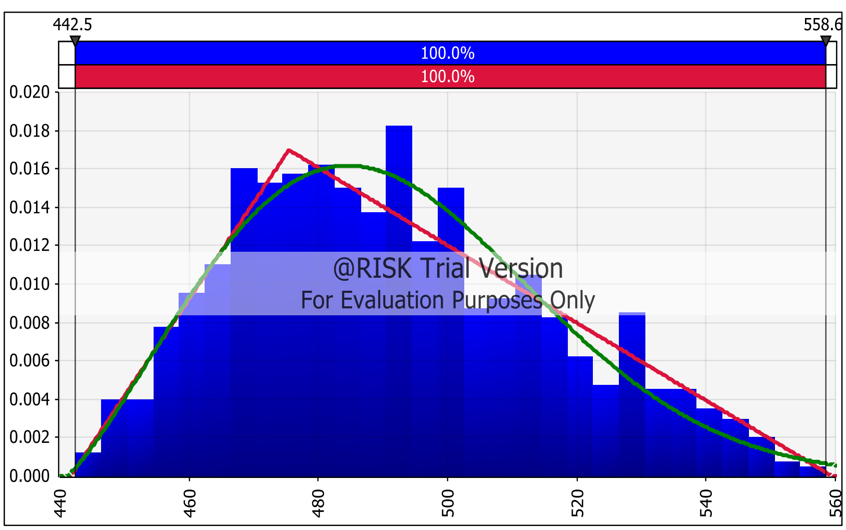


Figure 3.20: Variation in the Procurement Phase

Results for Update 1 (Case 2). Figure 4.14 represents the variation of the total project duration after applying the updated data, while Figure 4.15 shows the variation in the procurement phase only.

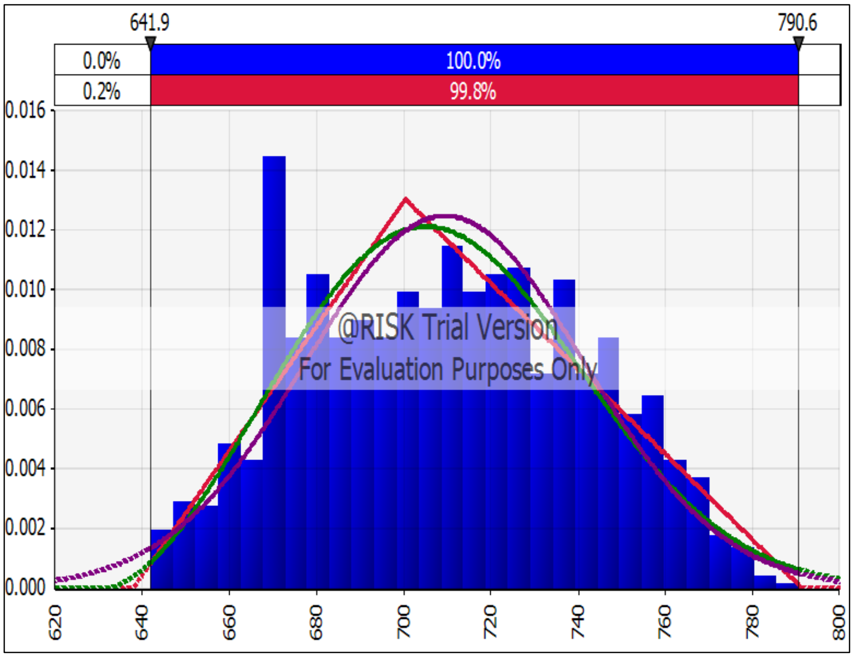


Figure 3.21: Variation in the Procurement Phase

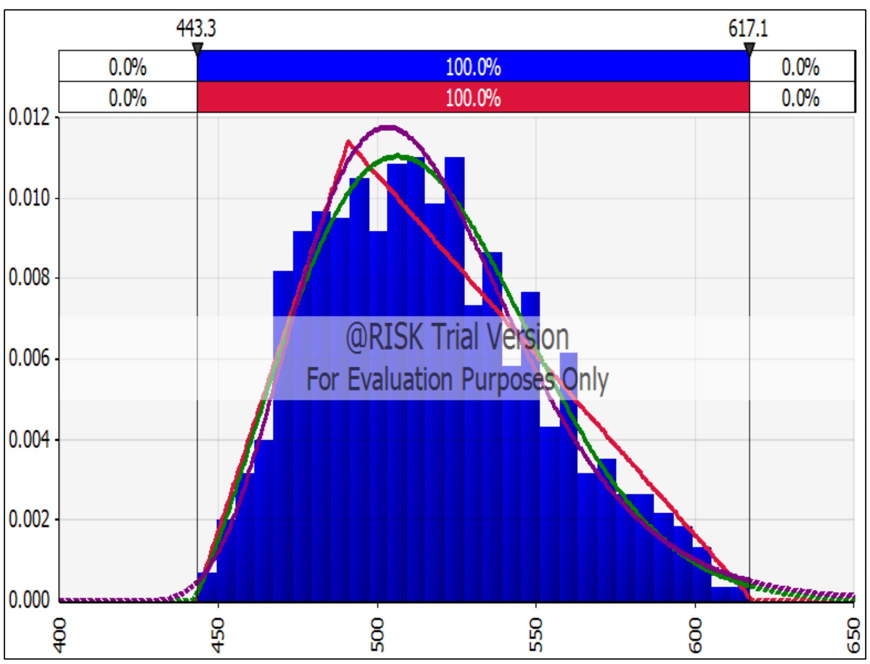


Figure 3.22: Variation in the Procurement Phase

Results For Update 2 (Case 1). Figure 4.16 represents the variation of the total project duration using the default probability data for the second case, while Figure 4.17 shows the variation in the procurement phase only.

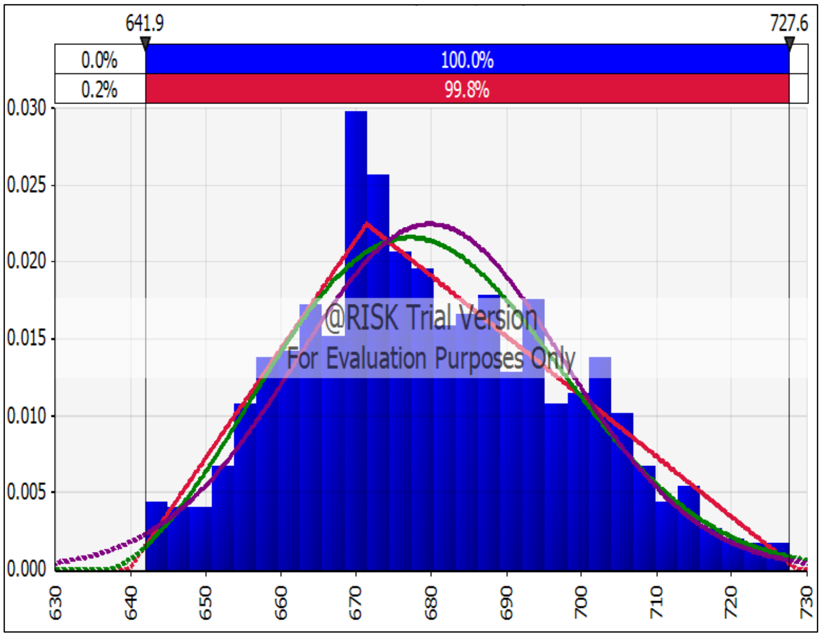


Figure 3.23: Variation in the Procurement Phase

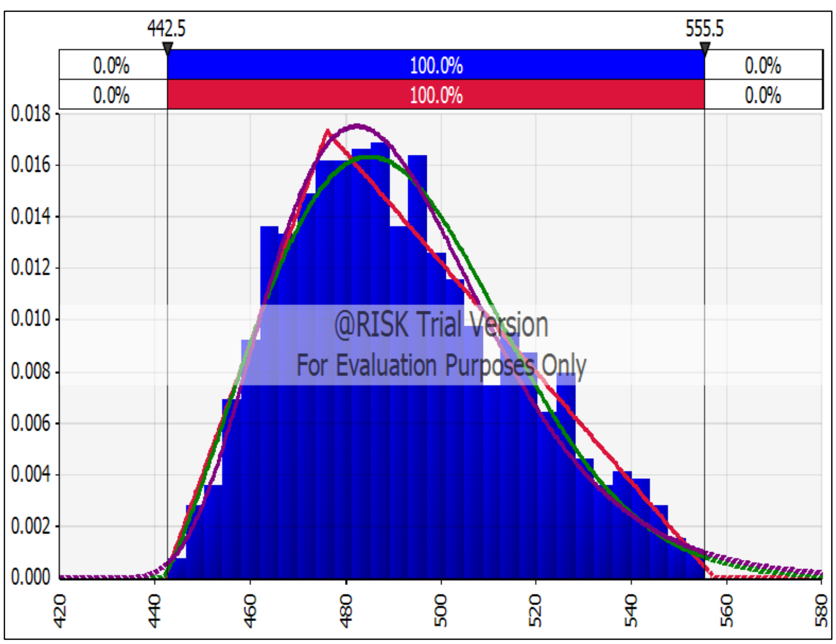


Figure 3.24: Variation in the Procurement Phase

Results For Update 2 (Case 2). Figure 4.18 represents the variation of the total project duration after applying the updated data for the second case, while Figure 4.19 shows the variation in the procurement phase only.

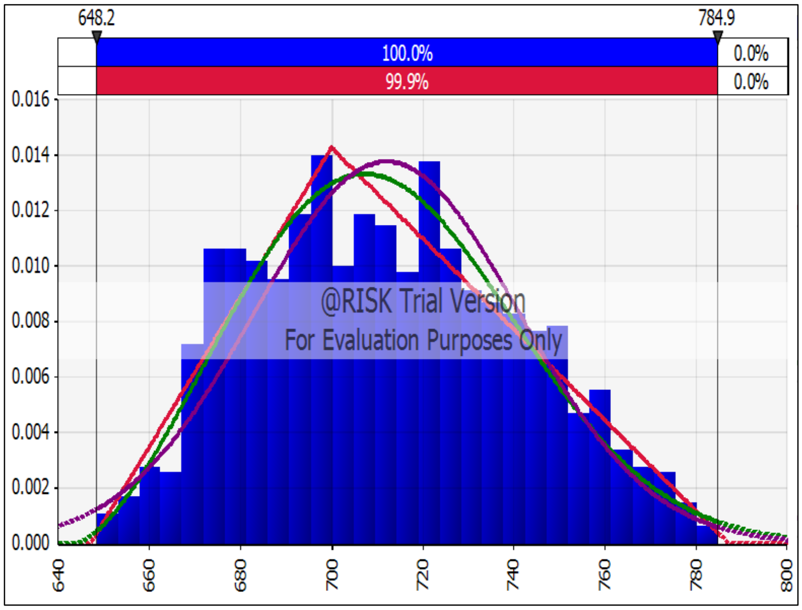


Figure 3.25: Variation in the Project Phase, Update 2 Case 2

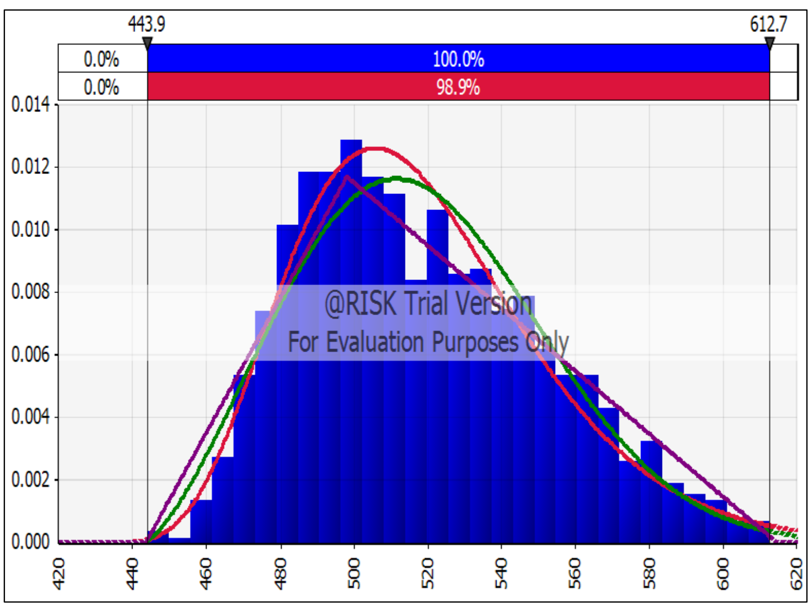


Figure 3.26: Variation in the Procurement Phase

4.8 Discussion

This work introduces a novel model that predicts the influence of major risk factors on the progress of construction projects. The model ensures instant detection for any risk factors arising during the execution of projects. The thesis demonstrates that automated supply chain visibility tools such as RFID tags, GPS tags, bar coding, and machine sensors enable the timely and accurate detection of progress delays, and lastly, the framework is being continually enhanced to refine the probability distributions for the risk factors and impact computations. Applying and verifying this system on different practical case studies will then follow.

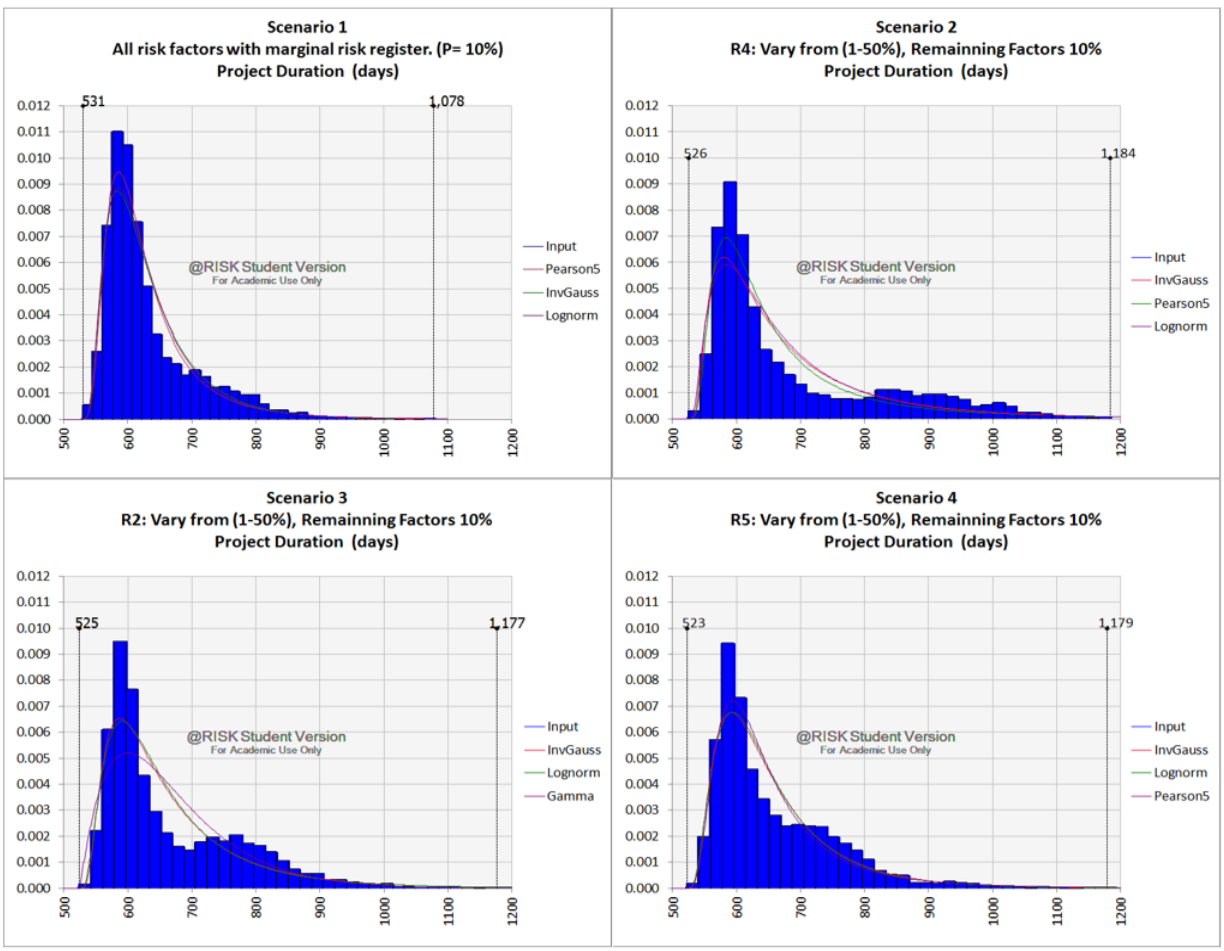


Figure 3.27: Different Scenarios for Validation

Chapter 5: Automatic Detection of SC Risk Related to Economic Conditions and Weather

5.1 Introduction

Construction management is a significant concept when evaluating the progress of any planned project, and contains several stages, especially in mega projects. The supply chain is one of the most important stages in which a project can be assessed. It has a great influence on the success of any project in meeting a deadline within the planned budget. It includes the planning and management of all activities involved in sourcing, procurement, and logistics, and also includes coordination and collaboration among partners, which can be suppliers, third-party service providers, and/or customers. Typically associated with the manufacturing industry, supply chain management (SCM) is not currently a mature area of investigation in the construction industry due to the varying nature of construction projects.

In construction projects, the late arrival of materials often leads to extensive delays that cause substantial overruns, thereby shrinking or eliminating project profit margins. To reduce the impact of unforeseen risk factors such as economic and environmental considerations that might influence the progress of a construction project, it is important to employ a support tool that can predict the influence of major risk factors in advance. However, because both the probability of the occurrence of risk factors and their likely impact continue to change throughout the duration of a project, late recognition of these changes creates more severe effects that are more difficult and costlier to manage. For these reasons, the model proposed in this thesis is designed to enhance risk management by helping decision-makers recognize the probability of the occurrence of risk factors during the early stages of a project.

The construction industry is a complex industry that involves different stakeholders and many key activities. Because of the industry's complexity, the supply chain is also very complex and involves different risks and uncertainties that can lead to major problems for projects. Because the supply chain life cycle can be long (spanning from design to manufacturing, transportation, and delivery), different risks apply in each phase. The risks for each phase need to be identified and quantitatively assessed and the risk level evaluated frequently in order to dynamically update the supply chain process. Currently, no research exists that looks at the risks involved throughout the whole supply chain lifecycle, and therefore, there is a need to dynamically quantify the risk factors in order to manage supply chains effectively and efficiently. While a great deal of effort has been devoted to the study of CSCs, including the effects of risk, to the author's best knowledge no studies have included consideration of the dynamic updating of the probability of risk events throughout a project as a means of effectively revising their impact on time and cost. To reduce the impact of unforeseen risk factors that may influence the progress of any construction project, it is important to have support tools that can predict the influence of major risk factors in advance. However, risk factors keep changing in their probabilities and impacts along a project's duration, and these changes will be more severe and have more influence if recognized later rather than earlier, and will be more difficult and costly to manage.

The primary objective of the work presented in this thesis is to create a model that automatically detects changes in the risks associated with a construction SC, with a focus on weather and economic factors and the quantification of their impact on construction time and cost as a means of assisting decision-makers in understanding key risk factors and the impact of changes in those factors with respect to the progress of construction projects. The detailed objectives are as follows:

1. Identify key risk factors and related quantitative parameters that affect the supply chain life cycle;
2. Develop an automated mechanism for detecting changes in risk values during an SC life cycle;
3. Develop a simulation model that takes into account the combined levels of uncertainty associated with the risk factors and then quantifies their impact on project time and cost;
4. Experiment with the developed model using real-life construction projects.

This chapter proposes a novel model that is designed to enhance risk management by helping decision-makers recognize the probability of the occurrence of risk factors during the early stages of a project based on dynamic risk factor variations. Accordingly, while many risk management tools exist to support SCM and project control and while many factors have been identified and investigated, the proposed dynamic character of the values in this thesis has not yet been proposed in the literature. This study looks at a selection of these factors and then, by developing a dynamic automated tool, investigates how they influence planning.

5.2 Economic and Environmental Probability Detection Framework

With the goal of improving construction supply chain management (CSCM), this research involves the development of a generic automated mechanism for updating the risk register and the probability of the occurrence of risk events in order to accurately quantify the impact on project time and cost. The proposed framework includes three main elements: (1) the identification of possible SC-related economic and environmental risks; (2) the automatic detection and updating of the probabilities associated with the risk factors; and (3) the production of sensitivity analysis reports for decision-makers. Figure 5.1 shows a schematic of the proposed framework, which incorporates the following components:

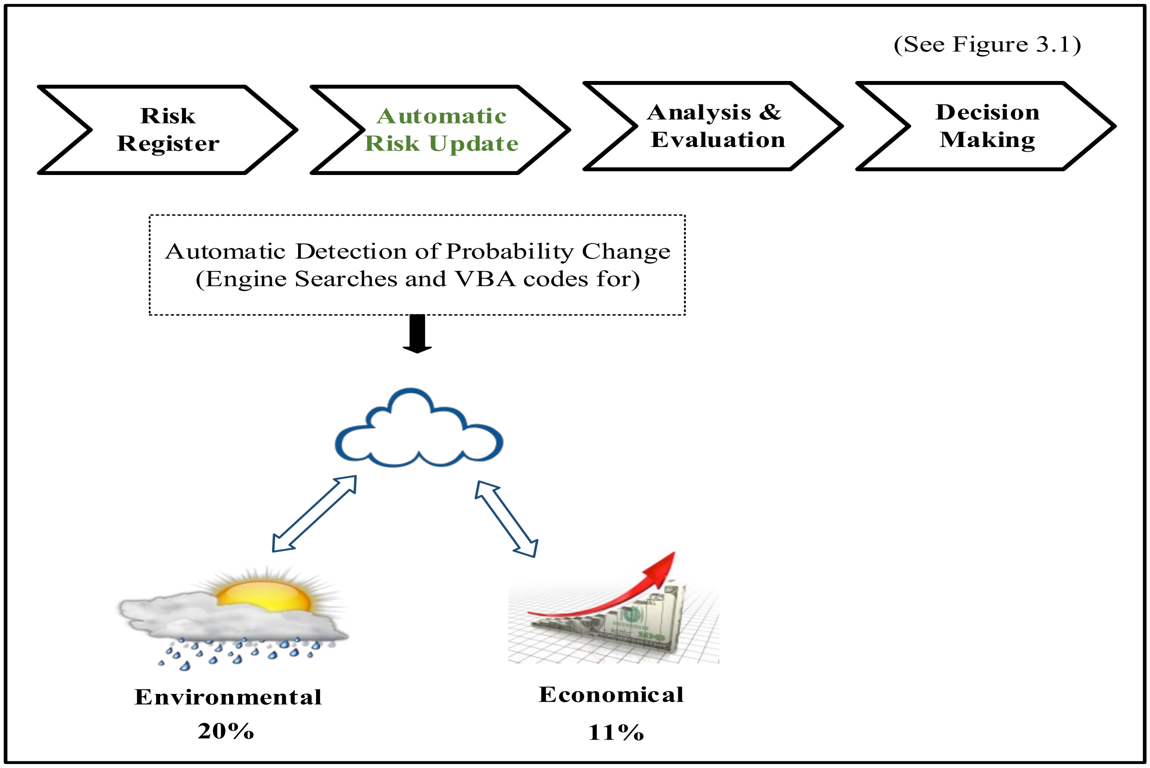


Figure 3.28: Automatic Detection Model (Economical & Environmental)

1. Risk Register: This feature includes identification of the key economic and environmental risk factors, along with the SC life cycle. It also indicates the categorization of the risk factors according to the SC lifecycle.

2. Automated Risk Updates: This section includes automated models for detecting changes in the probability of occurrence for each risk category.

3. Analysis and Simulation: This component includes the analysis and evaluation phase, for which a Monte Carlo simulation tool such as @Risk is employed.

4. Time and Cost Updates: This step involves the generation of sensitivity analysis reports, which help decision-makers better understand SC risks in advance.

The following subsections contain discussions of each these components:

a. Risk Register

This component has been developed based on an analysis of SC life cycles, which involve SC specification, design, procurement, construction, transportation, and site storage. The next step is the identification of SC risk factors. An extensive study of the literature was conducted in order to develop an initial list of key SC risk factors, and 42 factors were identified from the literature review. Based on expert opinion, this list was then filtered to include only the top 25 factors that influence a CSC. Most of these key factors are quantitative and can thus be evaluated at different stages during construction. Automating the frequent updating of these factors is also perceived as a means of greatly improving SC management and reducing the impact on project time and cost. However, for the purposes of this study, only the procurement and transportation stages have been considered. Some of the 25 factors, such as those related to changes in the weather, are deemed to be uncertainty factors that affect activity duration, while others, such as those associated with environmental hazards, are viewed as sudden risk events that impact multiple activities, as shown in Figure 5.2. Each type of risk (uncertainty and sudden events) is dealt with differently in the proposed model, as will be discussed later.

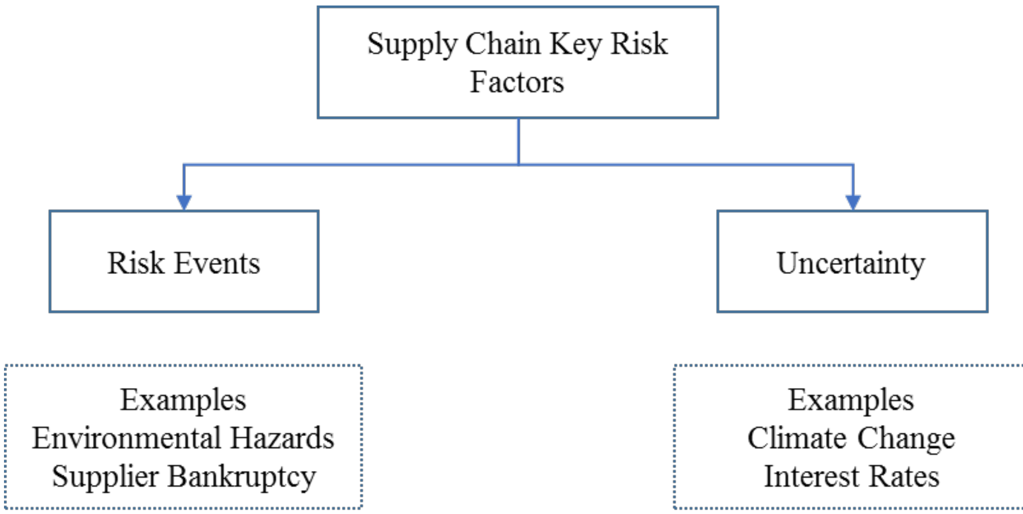


Figure 3.29: Types of Risk Factors Considered in the Research

b. Automated Risk Update

In this component, the default probability distribution for each risk factor is identified. For each SC lifecycle, several models are designed for the automatic collection of data from their sources, followed by the establishment of probability values or distributions. For example, for the transportation phase, a model was built for collecting weather data from the internet.

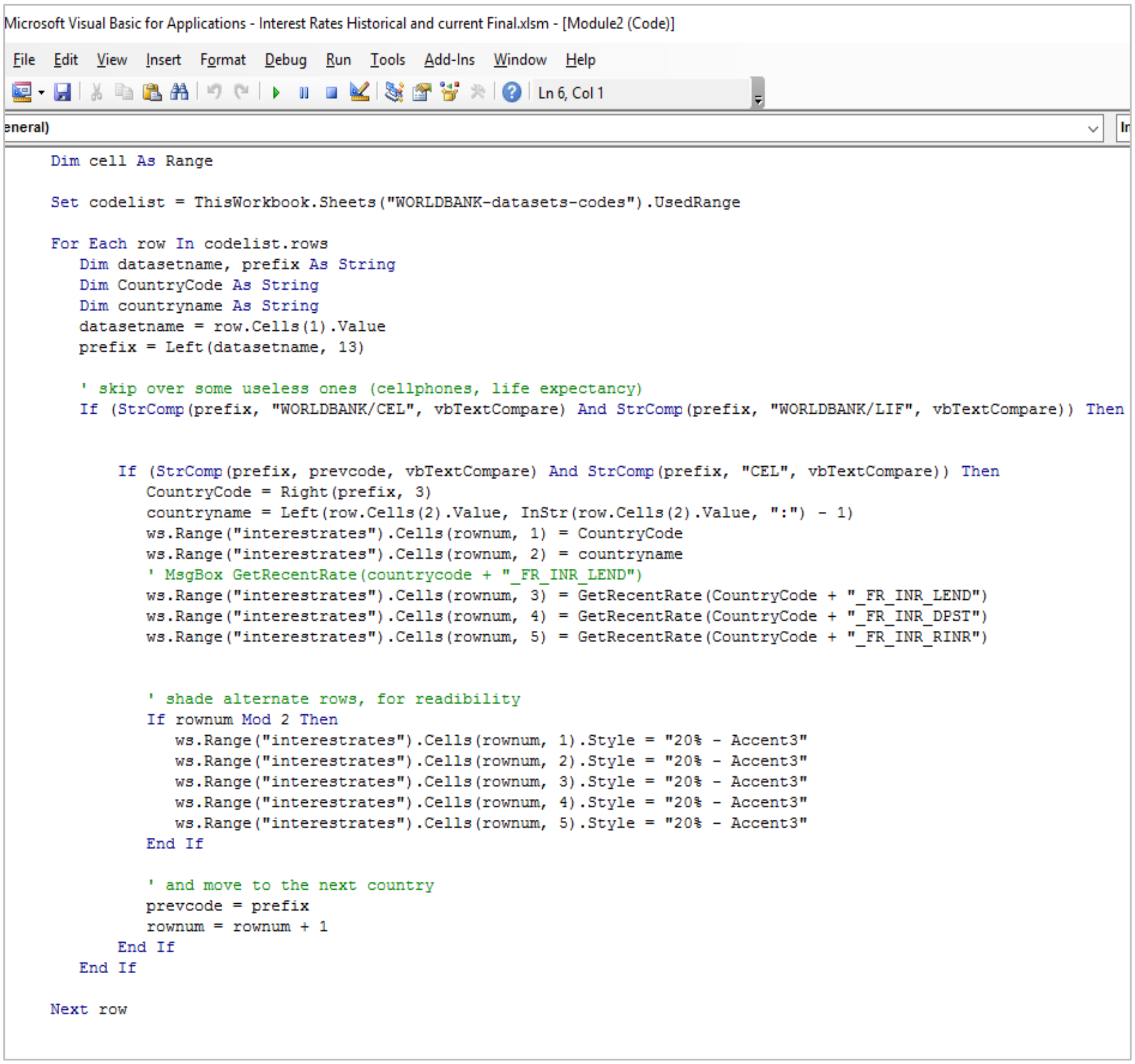
The code uses an Application Programming Interface (API) to perform the following actions within Excel:

1. To get the weather data, the API connects to a remote service, openweathermap.org, and then receives data from this service. The code loops through each line of the tasks and puts the information into Excel cells. The information is returned in XML format.
2. To get interest rate data and open exchange rates, the API connects to the website https://www.quandl.com/api/v3/databases/WORLDBANK/codes.csv for a list of the countries that have available data. For each country, there is a second call made to ask

for interest rates for that country. The data are captured and sorted, and then presented in a human-readable front page. Two types of data are available: (1) current rates for every country; and (2) historical information for any country listed.

3. To get bankruptcy information, the API is used to get lists of information about bankruptcies from sites such as http://www.bankruptcydata.com and http://www.ic.gc.ca. These sites provide data that are normally returned through programming interfaces. The data are picked through, looking for patterns in order to find useful information. Then a list of companies that are found on the page, with a search feature at the top of the page. Figure 5.3 shows a screenshot of the code used in the study. The remaining code is available in Appendix A.

Historical weather data were used as the benchmark for obtaining default probabilities, and weather forecast data were then employed for updating the default probabilities to the current probabilities. Research studies have proven the effectiveness of VBA in Excel for working with weather models; however, because of uncertainty about the efficacy of this approach for data related to other risk factors, other data collection methods were used. The results produced by the automatic risk update module include two different probability detection models for the CSC lifecycle. Each model was designed to automatically detect, quantify, and update the probability curves that are utilized in the SC risk register, and the developed risk register is then applied for the analysis of the impact on time and cost.



```
Microsoft Visual Basic for Applications - Interest Rates Historical and current Final.xlsm - [Module2 (Code)]
File  Edit  View  Insert  Format  Debug  Run  Tools  Add-Ins  Window  Help
Ln 6, Col 1
eneral)

    Dim cell As Range

    Set codelist = ThisWorkbook.Sheets("WORLDBANK-datasets-codes").UsedRange

    For Each row In codelist.rows
       Dim datasetname, prefix As String
       Dim CountryCode As String
       Dim countryname As String
       datasetname = row.Cells(1).Value
       prefix = Left(datasetname, 13)

       ' skip over some useless ones (cellphones, life expectancy)
       If (StrComp(prefix, "WORLDBANK/CEL", vbTextCompare) And StrComp(prefix, "WORLDBANK/LIF", vbTextCompare)) Then


           If (StrComp(prefix, prevcode, vbTextCompare) And StrComp(prefix, "CEL", vbTextCompare)) Then
              CountryCode = Right(prefix, 3)
              countryname = Left(row.Cells(2).Value, InStr(row.Cells(2).Value, ":") - 1)
              ws.Range("interestrates").Cells(rownum, 1) = CountryCode
              ws.Range("interestrates").Cells(rownum, 2) = countryname
              ' MsgBox GetRecentRate(countrycode + "_FR_INR_LEND")
              ws.Range("interestrates").Cells(rownum, 3) = GetRecentRate(CountryCode + "_FR_INR_LEND")
              ws.Range("interestrates").Cells(rownum, 4) = GetRecentRate(CountryCode + "_FR_INR_DPST")
              ws.Range("interestrates").Cells(rownum, 5) = GetRecentRate(CountryCode + "_FR_INR_RINR")


              ' shade alternate rows, for readibility
              If rownum Mod 2 Then
                 ws.Range("interestrates").Cells(rownum, 1).Style = "20% - Accent3"
                 ws.Range("interestrates").Cells(rownum, 2).Style = "20% - Accent3"
                 ws.Range("interestrates").Cells(rownum, 3).Style = "20% - Accent3"
                 ws.Range("interestrates").Cells(rownum, 4).Style = "20% - Accent3"
                 ws.Range("interestrates").Cells(rownum, 5).Style = "20% - Accent3"
              End If

              ' and move to the next country
              prevcode = prefix
              rownum = rownum + 1
           End If
       End If

    Next row
```

Figure 3.30: Screenshot of the API code

Examining the impact of each risk factor. In this step, each risk factor was studied in detail using information from the literature in order to obtain an accurate impact for each phase. An impact curve for each supply chain risk factor is the output of this step of the framework. An example of the impact of temperature and precipitation on achieving changes in productivity obtained from a study by Li et al. (2013) on risk assessment and impacts is shown in Figure 5.4. Different methods can be utilized to obtain the impact of each risk factor (i.e., predefined models from the literature, expert opinions, etc.). The impact curves were utilized to develop the supply chain risk register needed for the analysis and evaluation module. The reason for choosing this model is due to its ability to capture a reliable data for the impact, and based on expert opinions.

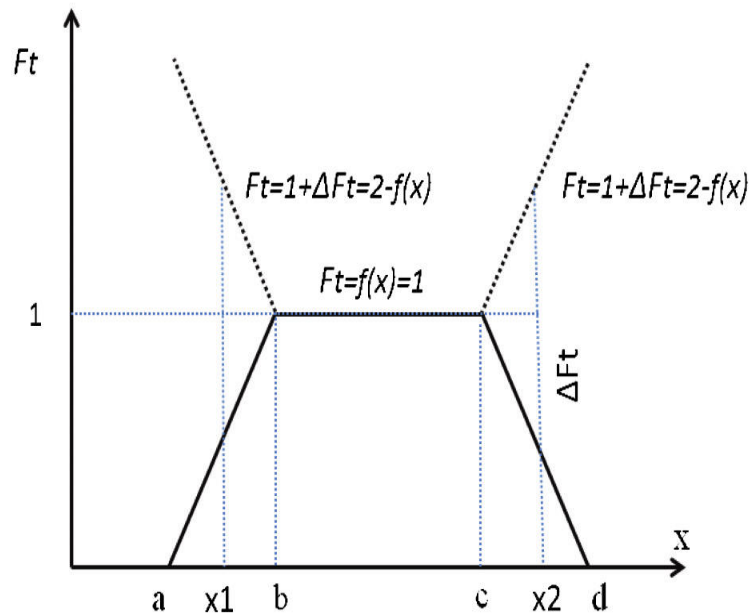


Figure 3.31: Impact Calculation for Temperature and Precipitation

Analysis and Simulation

The third module of the framework is called Analysis and Simulation, and the procurement and transportation phases provide examples for detailing this workflow. This module requires three input components: (1) a list of risk factors for each life cycle phase; (2) probability distribution curves; and (3) impact on each life cycle phase. These three types of input form the risk register required for the analysis of risk events. A Monte Carlo simulation approach is then applied to investigate the impact of these risks with respect to a given project's time and cost. An industrial project was employed as a case study for validating the two models and for determining the impact of SC risks on the project.

The output of the analysis and evaluation module consisted of the probability distribution functions for the project time and cost. These distributions are automatically updated to support decision-makers in their assessment of unforeseen factors related to their projects. As indicated in Figure 5.5, the analysis is applied for key SC activities in two stages. The first stage is implemented prior to the start of the project when the initial risk values are calculated based on default probabilities for the identified risk factors, and during the second stage, project execution, the automatic detection models are used for updating the probability of the occurrence of the risk factors and then updating them accordingly. The impact of these automatic detection models on the duration of the project is shown in Figure 5.5.

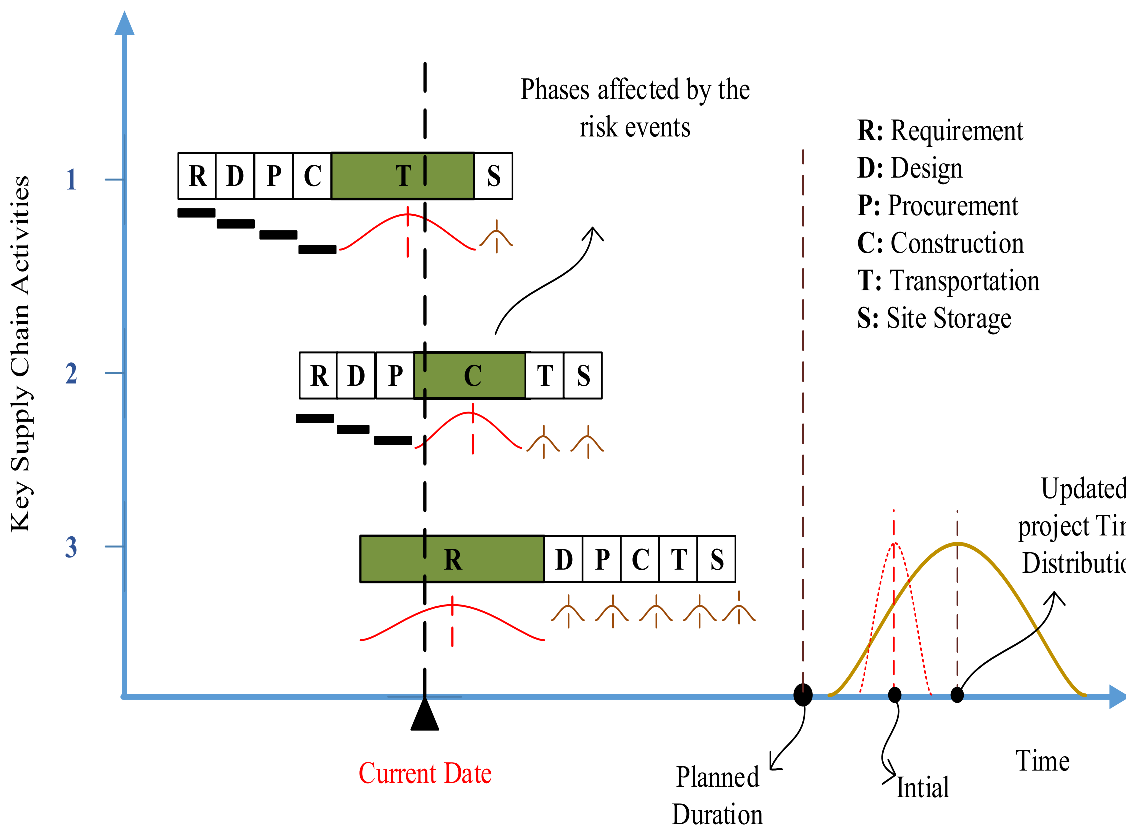


Figure 3.32: Risk Probabilities for Key CSC Activities

c. Time and Cost Update

In the final step, a Monte Carlo simulation tool (@Risk) is used to examine the impact of the risk factors on a real-life industrial project. This process starts by integrating the risk register and the project schedule in order to generate reports. These reports provide decision-makers with information about the effects of the unforeseen risk factors and their impact on the costs and schedules for their specific projects. The reason for using an MC simulation in construction is due to the fact that large-scale projects have many inherent uncertainties. Each unique construction project presents its own set of challenges due to the diversity of resources and activities.

The Monte Carlo simulation is utilized to perform various experiments on a model by using inputs obtained by sampling from input probability distributions. The probability distribution function (PDF) was used for calculating the probability that the random variable would fall into a particular interval (Equation 1).

$$\Pr(a < x < b) = \int_a^b f(x).\,dx \qquad (1)$$

Figure 8 illustrates an example of a PDF, and represents the probability based on the area under the curve. The Monte Carlo simulation method was used for estimating the output (Y) of a model with random input variables (X_1, X_2, X_3,…,X_n) (Figure 8). The number of iterations, k, depends on the level of accuracy that is required in the model.

$$X = \frac{\sum_{i=1}^{n} Yi}{n} \qquad (2)$$

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(Yi - Y)^2 \qquad (3)$$

The Cumulative Distribution Function (CDF) is typically used for finding the probability of not exceeding a given threshold. Equation 4 defines the CDF function of a random variable X. The CDF can be calculated based on PDF f(x) using Equations (4, 5):

$$Fx(x) = \Pr\{X < x\} \quad (4)$$

$$F(x) = \int_{-\infty}^{x} f(t).\, dt \quad (5)$$

Considering a finite number of random samples from k experiments, the CDF function can be estimated with Equation 6:

$$Fx(t) = \frac{\text{Number of Samples}}{n} \quad (6)$$

The inverse of the CDF is used for finding an arbitrary quantile. Figure 9 indicates the use of CDF F(x) for finding the 90th quantile of a random variable.

5.3 The Weather and Economic Related Risk Update Case Study

This section describes the use of an industrial project for validating the proposed model. The project entails the supply, erection, and O&M of a gas turbine at a power and desalination plant. This megaproject includes a number of milestones and key activities, and is a fast-track type of contract project with three main phases: (1) engineering; (2) procurement; and (3) construction and erection (as shown in Fig 5.6). For many activities, the nature of this project means that the timing of these three main phases overlaps. The focus of this study was on the key activities that require the study of SC risk management. These activities are essential for the project and have a significant role in its completion. Process piping was chosen for illustration, as it is a common element of most industrial construction projects. More importantly, process piping is a segment of the construction industry that is known to suffer from the effects of uncertainty in the supply network. The project contains of 982 activities (see Appendix A), and the planned project duration is 641 days.

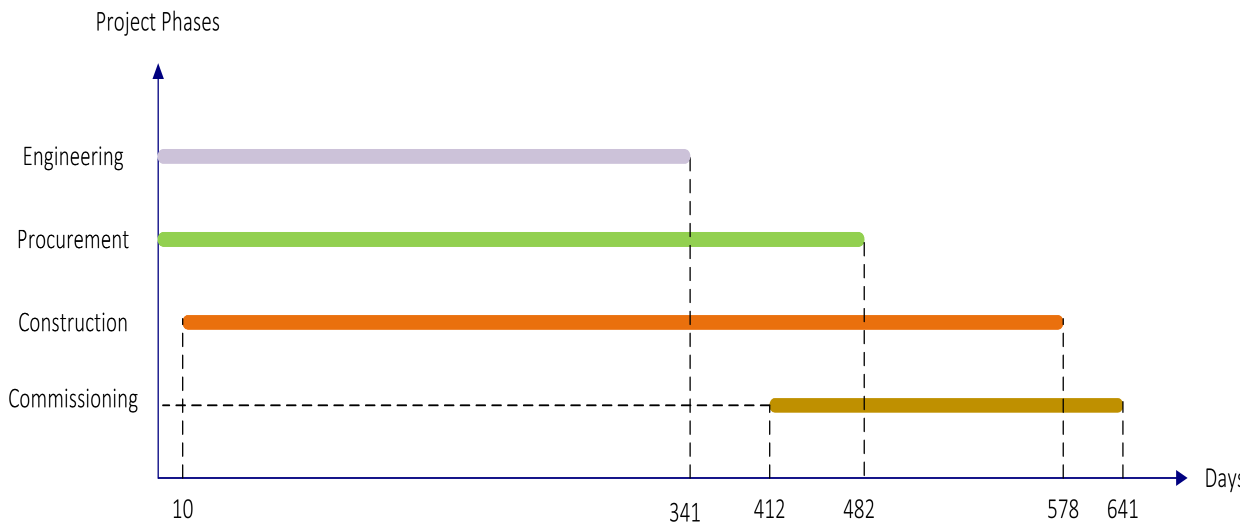


Figure 3.33: Bar Chart of the Project Phases

The flow chart shown earlier was utilized to validate the proposed model and indicates the four main steps for applying the analysis and producing the results. The first step is the identification of the SC risk register, with a focus on economic and environmental risk factors. The second step is the use of VBA code for automatic collection of the data for both the economic and environmental risk factors. The third step is the calculation and updating of the probability of occurrence for each SC risk factor. The fourth step is the application of these probability values to the risk register. In this final step, a Monte Carlo tool (@Risk) is utilized for the examination of the impact of changes in the probability associated with each risk factor with respect to the specified project duration.

5.3.1 Risk Factors

As shown in Table 5.1, the analysis begins with the identification of the economic and environmental risk factors obtained from the first module in the research framework. As explained in Section 3.2, each risk factor is categorized under only one life cycle stage; however, the same approach used for the calculation of weather-related risk factors can be modified and applied for the remaining phases. These factors might not have the most influence on a project's delays; however, these factors were considered for the sake of validating the proposed model. The factors related to changes in the weather are considered uncertainties with respect to the duration and cost of key SC activities. On the other hand, environmental hazard factors are regarded as risk events with a low probability of occurrence and a high impact. Based on this principle, interest rates and exchange rates are viewed as uncertainties, while supplier bankruptcy and price changes are treated as risk events.

Table 5.1: Economic and Environmental Risk Factors

Risk Factors	**Type of Risk**	**SC Life Cycle**					
		R	D	P	C	T	S
R1: Price Change	2			X			
R2: Supplier bankruptcy	2			X			
R3: Market Condition (interest, exchange)	1			X			
R4: Environmental Hazards	2					X	
R5: Climate Change	1					X	

* 1: Uncertainty 2: Sudden event

** R: Requirement, D: Design, P: Procurement, C: Construction, T: Transportation, S: Storage

Two sets of data are used in the analysis: (1) historical data, for obtaining the marginal probability calculations to be used as the benchmark for the model; and (2) forecast data, which are required for the continual updating of changes in the probability. Details of both sets are included in the explanation in Section 3.3.

5.3.2 Data Collection for Marginal and Conditional Probabilities

Historical weather data, the first set of environmental data, are available from several online sources; however, the data for this study were extracted from two main sources: Environment Canada and Open Weather Map. VBA in MS Excel is a powerful tool for the automatic extraction of historical weather data. More than 20 years of data were used in this study. A sample of the extracted historical data is shown in Table 5.2.

The focus was on two significant weather parameters: total precipitation and temperature. These sets of data were required for the calculation of the marginal degree of probability to be used as a benchmark for the weather model. Mean temperature values were employed for the development of a probability distribution function (PDF) for each month of the past 20 years, and the total precipitation values were used for the creation of a PDF for precipitation.

Table 5.2: Sample of Historical Precipitation and Temperature Data

Date	Month	Total Rain	Total Snow	Total Precipitation	Max Temp	Min Temp
Jan-87	1	3.1	50	53.1	13.6	-25.7
Jan-98	1	51.7	40.4	92.6	10.2	-14.9
13-Jan	1	52.2	22.8	68	13.5	-20.8
Jun-86	6	130.4	0	130.4	28.6	1.9
Jun-93	6	158.4	0	158.4	29.1	6
13-Jun	6	166.6	0	166.6	33.1	7.4

Historical economic data, the second set of data, are also available from several online sources; however, the data for this study were extracted from two main sources: Open Exchange and Quandl. A sample of the extracted historical data is shown in Table 5.3. The focus was on currency exchange, interest rates, and supplier bankruptcy. These sets of data were required for the calculation of the marginal degree of probability to be used as a benchmark for the economic model.

Table 5.3: Sample of Extracted Historical Exchange Rate Data

Time	US Dollar	Canadian Dollar	Euro	British Pound
	USD	CAD	EUR	GBP
00-11-01	1.000	1.527	1.164	0.691
01-11-01	1.000	1.593	1.105	0.683
02-11-01	1.000	1.558	1.003	0.639
03-11-01	1.000	1.318	0.863	0.591
04-11-01	1.000	1.222	0.785	0.546
05-11-01	1.000	1.179	0.833	0.567
06-11-01	1.000	1.133	0.783	0.524
15-11-01	1.000	1.308	0.907	0.647

The second set of data is the weather forecast data. Using the sources identified earlier, VBA enabled the design of a code for extracting the weather forecast data for any given city for 14 days, and an example of the extracted data appears in Table 5.4. The forecasted data take into consideration the historical data for any given factor. For example, when the weather is updated using the forecast model, the model uses historical data as a source for the update. The weather forecast data were required for the calculation of the conditional probability values. The updates to and changes in the probability are necessary for the automatic updating of the marginal probability and risk values. Supplier bankruptcy and weather hazards are dealt with as risk events. For supplier bankruptcy, the code connects with the search engines and looks for any supplier bankruptcies. At the same time, a different application looks for any environmental hazards that might impact the process of the delivery of any shipped items.

Table 5.4: Weather Forecast Data for the City of Toronto

Dates	Temperatures c		Wind		Precipitation	Pressure
	Max	Min	Speed (km/h)	Direction		(psa)
29-3-15	0.91	0.82	7.51	SSW	0.17	1007.61
30-3-15	5	-2.03	8.62	WNW	2	1001.76
31-3-15	3.13	-5.6	2.32	SE	2.84	1005.49
1-4-15	0.98	-8.56	2.38	S	5.47	1012.9
2-4-15	9.33	2.86	9.37	SW	8.24	996.61
3-4-15	1.91	-2.99	5.8	NE	0.12	1012.37
8-4-15	-2.18	-4.32	10.27	WNW	0.61	1009.03
9-4-15	5.77	-1.64	8.14	WSW	4.7	997.4
10-4-15	0.44	-6.65	8.13	NW	0.22	1010.95
11-4-15	3.16	-5.83	5.65	SE	0.39	1018.85
12-4-15	10.09	-0.36	8.11	WSW	4	998.89
13-4-15	3.32	0.47	7.01	NW	0.11	1008.3

5.3.3 Calculating and Updating the Probabilities

To calculate the probability values for the weather change risk factor, the extracted data were fitted into different statistical distributions. Figure 5.7 contains the best-fit distribution for the data derived from Table 5.2 for each weather parameter used in the study. Using the Bestfit statistical software, a best-fit distribution was obtained based on the data entered.

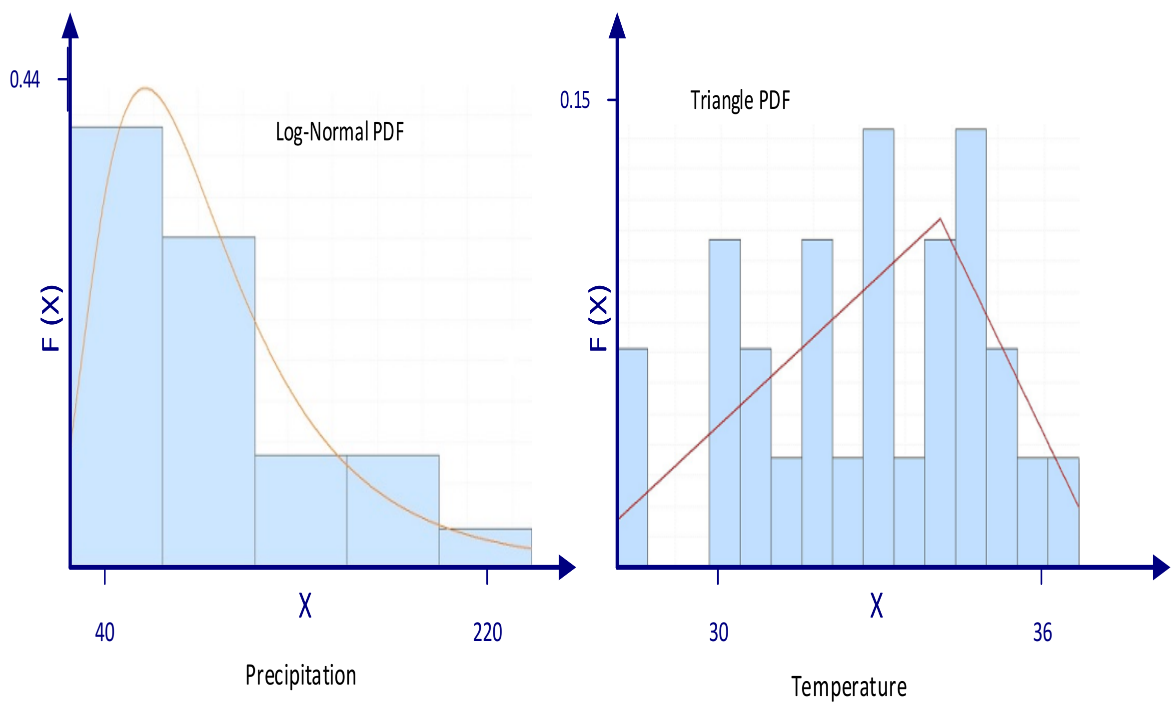


Figure 5.7: Probability Results for Precipitation and Temperature

The example provided in Figure 5.8 shows that the best-fit distribution for precipitation is log-normal, whereas the best-fit distribution for temperature is triangular. The probability of obtaining any value X can be determined using the defined distributions along with their parameters, as illustrated in Figure 5.8. Statistical software is helpful for the automatic calculation of the probability values, as shown in Figure 13, which illustrates two examples: the probability that the total precipitation level will be between 100 and 150 is 19.6 %, and the probability of any given temperature being between 30 °C and 35 °C is 75 %.

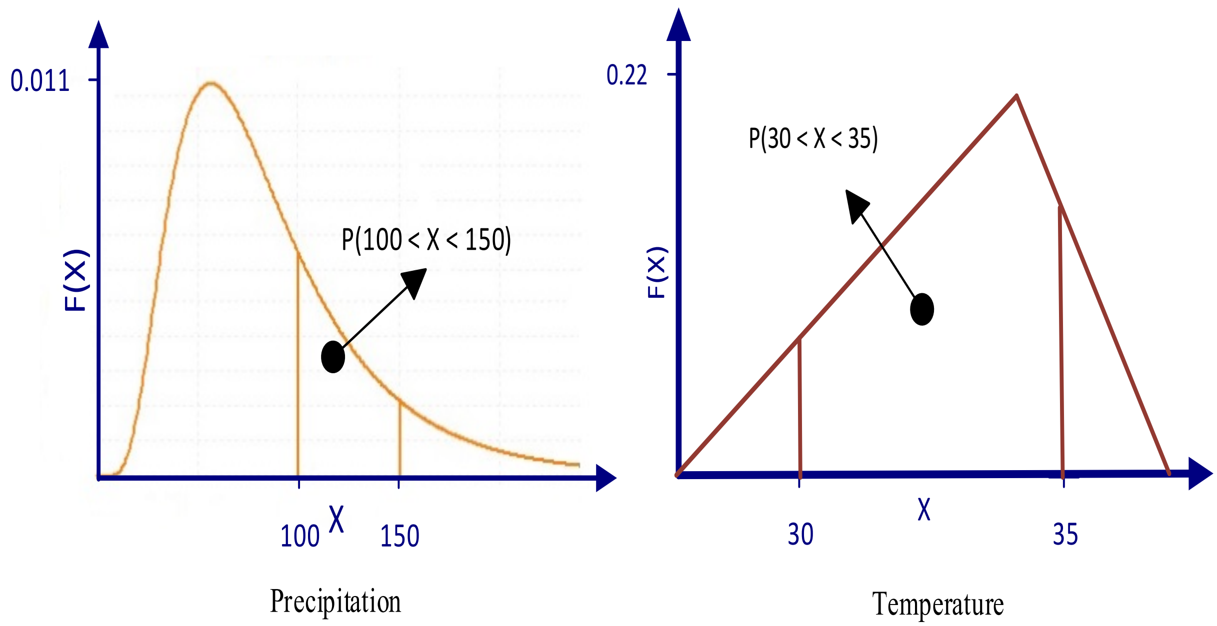


Figure 5.8: Probability Distribution Functions for the Historical Data

Figure 5.9 depicts two different probability distribution functions. The blue one represents the last 20 years of historical temperature data for the city of Toronto. This distribution was used for calculating the magnitude of the risk prior to the beginning of the project. The second distribution, in red, represents the actual forecasted data for the same location. The second distribution was employed for updating the risk values related to the weather change factors.

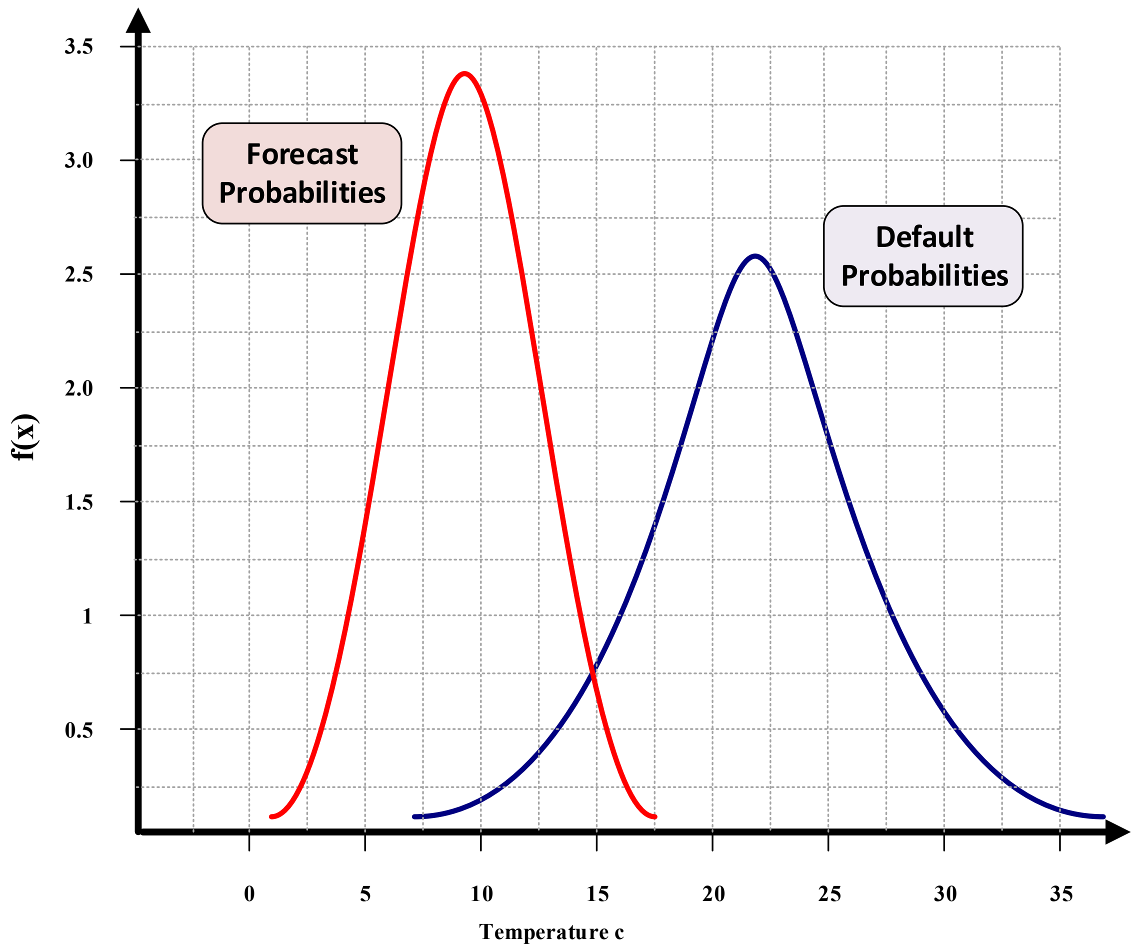


Figure 5.9: Comparison of Environmental Data: Historical (Blue) and Forecasted (Red)

Figure 5.9 reveals how the forecasted data (for conditional probabilities) can differ significantly from the historical data (for marginal probabilities). For example, based on the historical PDF, the expectation would be that the temperature values are distributed normally with a mean of 22°C and a standard deviation of 5°C, while the forecasted PDF calculated from recent data would lead to the expectation of more realistic temperature values distributed normally with a mean of 9°C and a standard deviation of 2.5°C. The results obtained when the forecasted data are used thus provide definitive proof of the value of automatic updates.

5.4 Time and Cost Impacts

After all possible variations in the duration of activities due to risk factors have been defined and the probability of the occurrence of each risk event has been applied, along with its impact, @Risk simulation software provides an effective means of examining the effect of these risk factors on the time and cost associated with project completion. One result of this process is that, rather than obtaining the deterministic project duration using a CPM approach, a probability distribution range is developed. For the test case, the software was set to run 5,000 trials with 10 different simulation cycles.

The reason for choosing a large number of runs is to ensure that the simulation covers all possible ranges of the input affected by the uncertainty. The planned duration of the project was 550 days; however, consideration of the impact of risk events changes the planned deterministic value of 550 days to a range between 520 days and 980 days, distributed with a mean value equal to 610 days, as shown in Figure 5.10.

These results represent essential information that will assist project managers or decision-makers in understanding unforeseen changes to their plans so that they can take early action. The automatic and continual updating of these results along the project life cycle will also provide them with continual updates and feedback with respect to the progress of their projects.

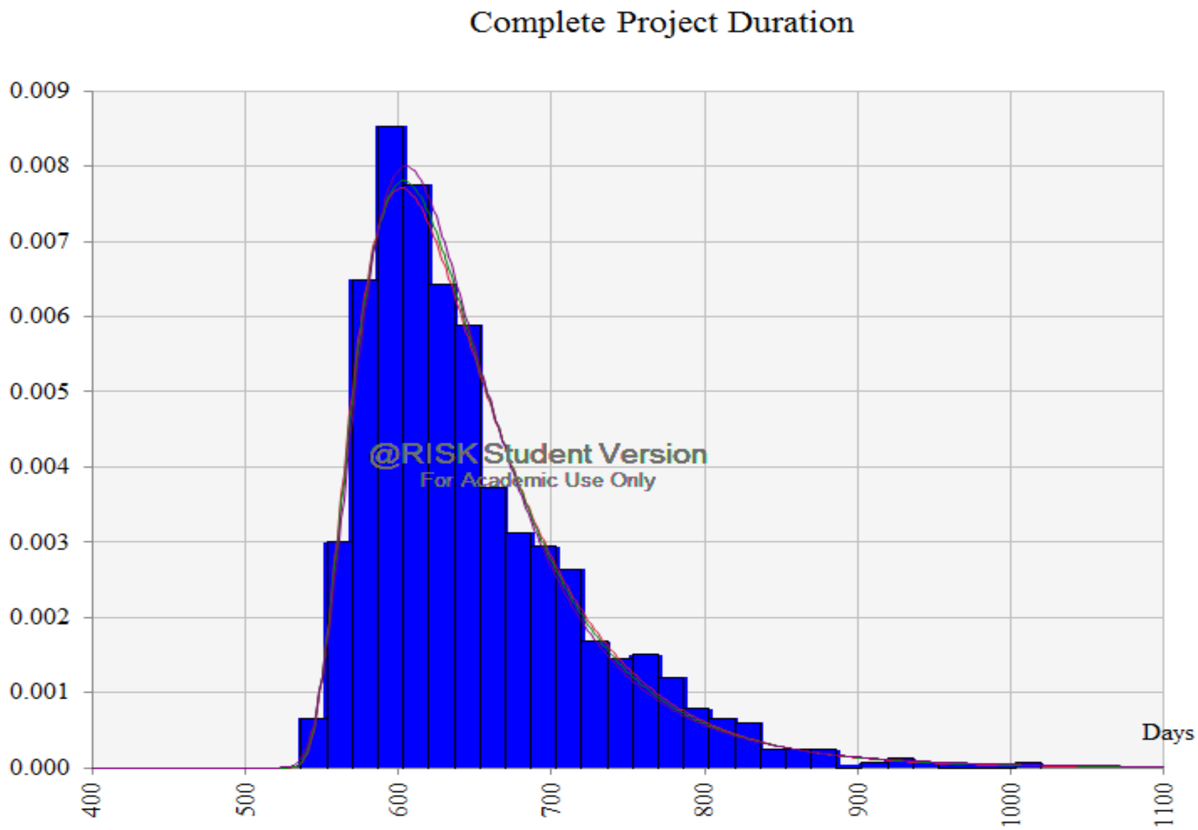


Figure 5.10: Probability Distribution Function for Variations in Project Time due to Risk Factors

Finally, a tornado diagram was generated in order to determine the risk factor that most contributes to project delays due to the given uncertainties and events. Tornado Diagrams are very important for defining major factors and how much they contribute to project delays and cost overruns. Figure 5.11 shows that weather hazards, suppliers' bankruptcy, and price changes contribute the most to delays. For example, supplier bankruptcy has an impact variation for a project delay between 746 and 866 days. The remaining factors have a smaller influence on project delays.

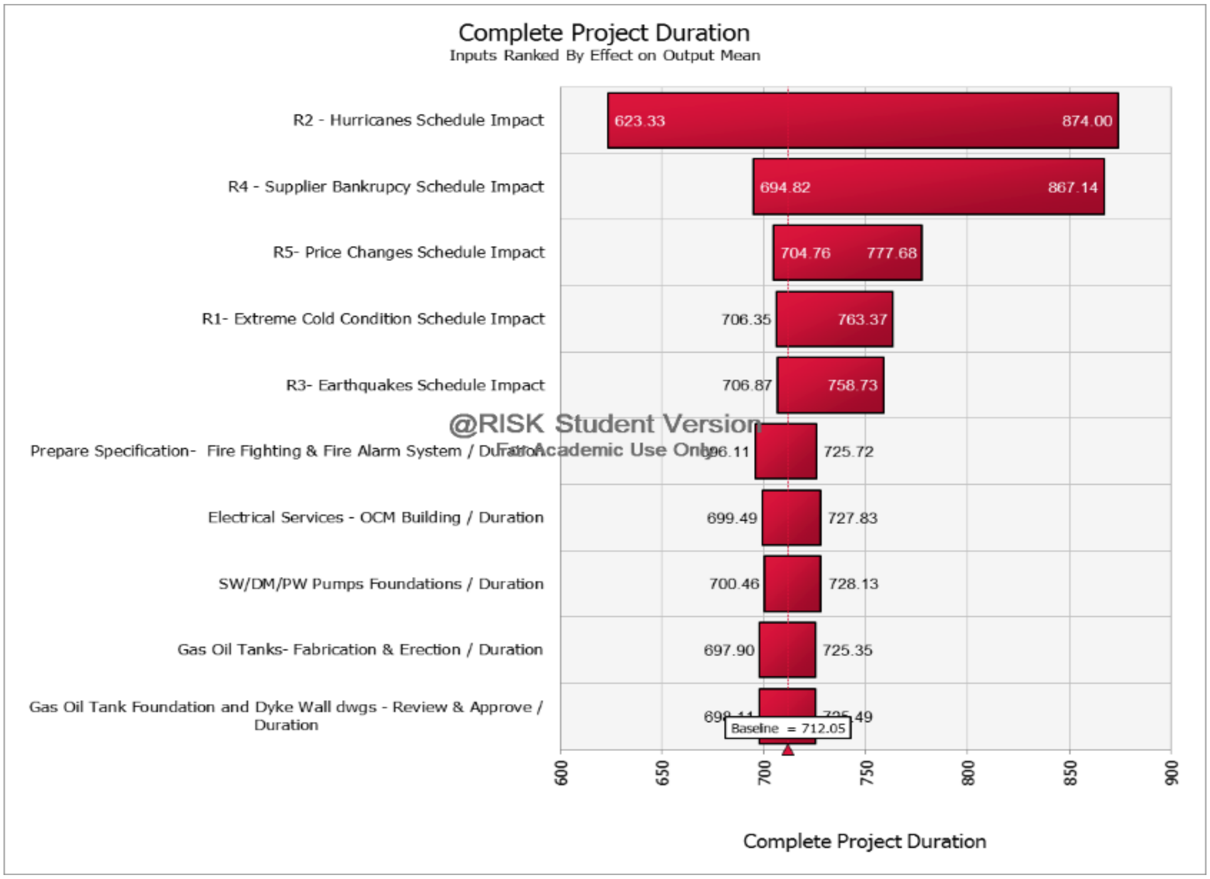


Figure 5.11: Tornado Diagram for Project Delays

5.5 Sensitivity Analysis

Numerous experiments were conducted in order to examine the effectiveness of the model for a variety of scenarios, with the goal of validating the importance of the automatic detection of changes in the probability of the occurrence of SC risk factors and their impact on the project. Table 5.6 contains a list of different scenarios implemented, along with their associated impacts on the project schedule.

Table 5.6: Sensitivity Analysis for Model Validation

	Description	Mean (Days)	Parameters
1	P = 1% with fixed I = 100%	506	Lognormal (87, 28, Risk Shift (506))
2	P = 5% with fixed I = 100%	515	Lognormal (95, 47 ,Risk Shift (515))
3	P = 10% with fixed I = 100%	523	Lognormal (109, 73, Risk Shift (523))
4	P = 15% with fixed I = 100%	524	Lognormal (133, 96, Risk Shift (524))
5	P = 20% with fixed I = 100%	514	Lognormal (166, 111, Risk Shift (514))
6	P = 30% with fixed I = 100%	535	Weibull (1.7, 214, Risk Shift (535))
7	P = 40% with fixed I = 100%	526	Weibull (2, 279, Risk Shift (526))
8	P = 50% with fixed I = 100%	519	Weibull (2.5, 342, Risk Shift (519))
9	I = 100% with default P	514	Lognormal (166, 111, Risk Shift (514))
10	I = 120% with default P	520	Lognormal (183, 148, Risk Shift (520))
11	I = 140% with default P	521	Lognormal (206, 185, Risk Shift (521))
12	I = 160% with default P	514	Lognormal (237, 214, Risk Shift (514))
13	I = 180% with default P	524	Lognormal (257, 279, Risk Shift (524))
14	I = 200% with default P	527	Gamma (1.4, 187, Risk Shift (527))
15	Random P with fixed I	527	Gamma (2.6, 67, Risk Shift (526))
16	Random I with fixed default P	529	Gamma (1.7, 137, Risk Shift (529))
17	Random P and I	529	Gamma (1.8, 133, Risk Shift (529))

5.6 Discussion

To reduce the impact of unforeseen risk factors, it is important to have support tools that predict in advance the influence of major risk factors on the progress of construction projects. However, risk factors keep changing in their probabilities and impacts along a project's duration. These changes will be more influential and costly to manage if only recognized at a late stage of a project. This research aims to improve construction supply chain management by developing an automated mechanism for updating the risk register and the probability of the occurrence of risk events. It has identified the key risk factors (i.e., Supplier Bankruptcy and Environmental Hazards) and their related quantitative parameters in order to assign uncertainty to key SC activities. The proposed model in this thesis has demonstrated that automatic detection of changes in probabilities for major risk factors related to supply chains can be a valuable asset for construction projects. The Monte Carlo simulation model @Risk has demonstrated the impact of uncertainty associated with risk factors in on project's time and cost. The model was tested and validated on a real-life industrial case study. Figure 5.12 demonstrates the probability distribution functions for the project duration considering the changes in probabilities from 1%, 10%, and 50% for the risk factors R2 and R4.

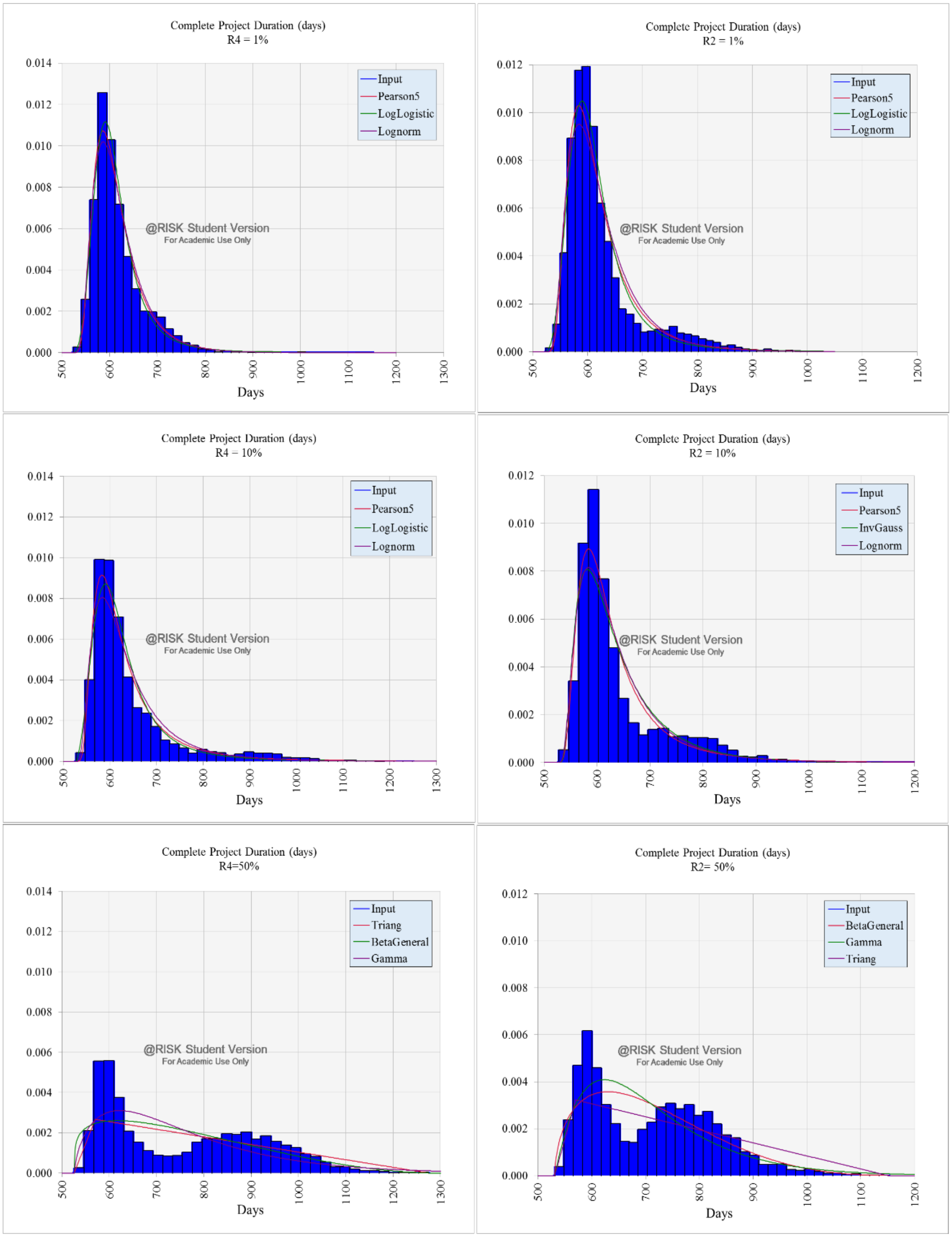


Figure 5.12: PDF for the Project Duration by Changing in the Probability of R2 and R4

Based on the analysis of the Monte Carlo simulation performed by @Risk, the tornado diagram shows that two risk factors contribute to project delays including supplier bankruptcy (R2) and environmental hazards (R4). A default probability of 10% was applied as a benchmark for the planning of the project duration. The default probability was utilized for the two main risk factors R2 and R4, and applying the 10% probability to the risk factor R2 revealed that there is a 50% chance that the project can be completed in 608 days or less, as shown in Table 5.7.

Table 5.7: 50th and 90th Percentile for Project Duration

Risk Factors	50th Percentile Completion Time (days)			90th Percentile Completion Time (days)		
	*P = 1%	P = 10%	P = 50%	P = 1%	P = 10%	P = 50%
R2: Supplier Bankruptcy	602	608	709	727	780	863
R4: Environmental Hazards	602	609	738	695	776	985

*P: Probabilities of occurence

During the execution of the project, changes in the two unforeseen risk factors R2 and R4 could significantly affect the duration. Updating the probability continuously helps in recognizing and minimizing the impact of these risks in the early stages. For example, by increasing the probability from 10% to 50% for R2, there is a 50% chance that the project can be finished in 709 days or less with about a 20% increase in the project duration, compared to 608 days. Likewise, there is a 50% chance that the project can be completed in 602 days or less by reducing the probability to 1%. For the Environmental Hazards risk factor R4, there is a 50% chance of completing the project in about 609 days or less when applying the 10% benchmark probability. When the probability is increased to 50% there is a 50% chance of completing the project in 738 days or less with about a 20% increase in the duration. Reducing the probability to

1% can lead to a reduction in duration. The same approach is utilized for the 90th percentile for the project completion time, as shown in Table 5.7. Figure 5.13 represents the cumulative distribution function for the project duration considering a change in an individual risk factor. For example, the curve that represents the probability of the risk factor R4 being equal to 50% shows the importance of continuous updating and how it impacts project duration.

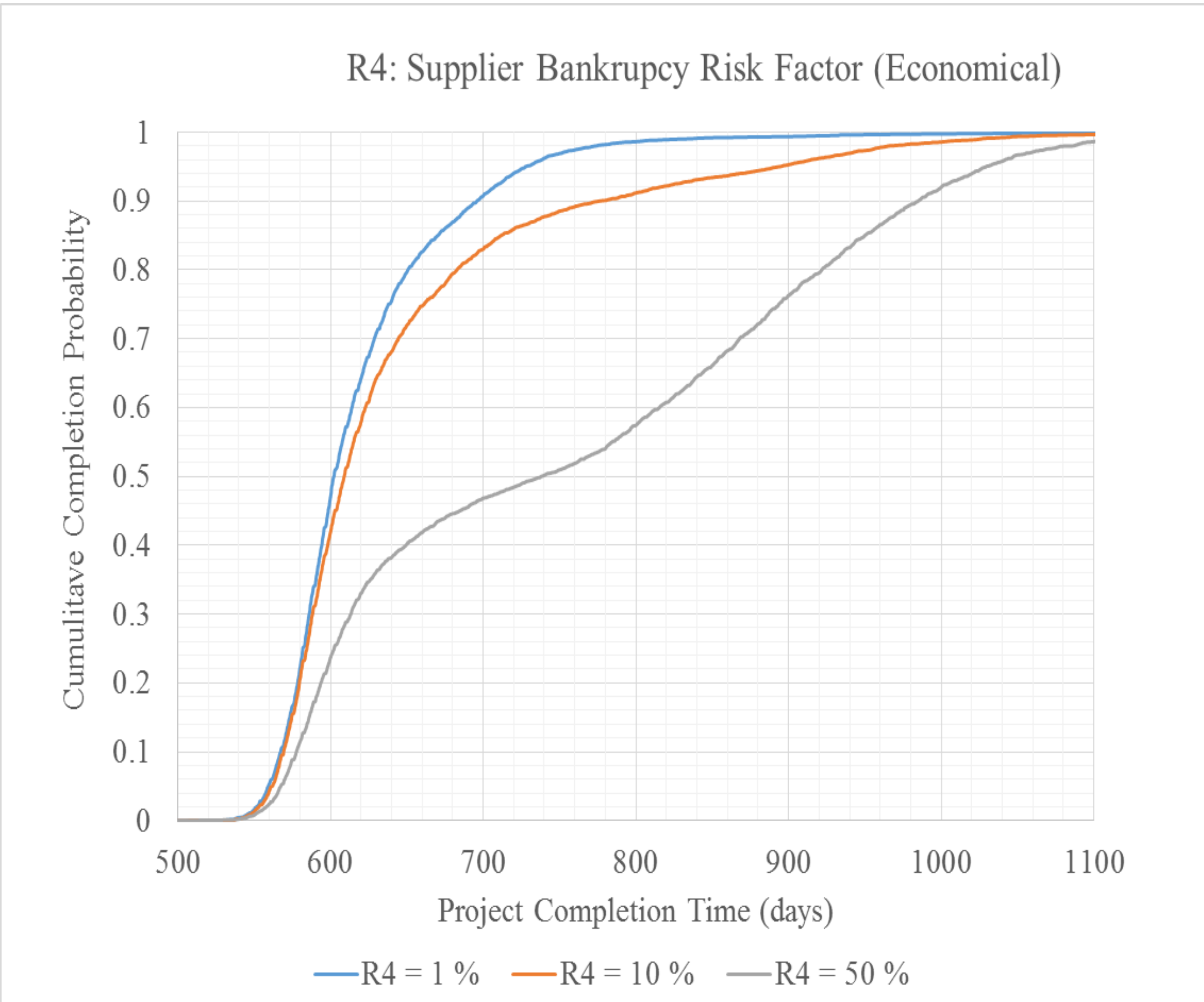


Figure 5.13: Cumulative Distribution Function for Project Duration Considering Change in R4

Chapter 6: Concluding Remarks

6.1 Summary and Conclusion

The goal of this research has been to develop a model that dynamically detects the probability changes for supply chain risk factors. The importance of effective materials management on construction projects cannot be ignored, and as a result, improving the processes of a supply chain is identified as having the potential to significantly affect the performance of the project as a whole. Nonetheless, ineffective materials management remains a primary cause of poor performance in construction projects. A possible cause of this poor performance is the existing methods of information collection and transfer. Manufacturing sectors have implemented new management approaches related to their supply networks, and while these changes have successfully improved the efficiency of their supply network operations, efforts to introduce similar changes in construction supply networks have not been as successful due to the overall complex and unique nature of construction projects and their associated supply chains in general. The integration of automatic detection methods for probability changes within construction supply networks, however, has shown a substantial ability for improving materials management on construction projects.

The overall objective of this thesis was to investigate the impact of dynamic detection of changes in probability for SC risk factors on the construction management process. A simulation approach was used as the main approach for investigation, and the developed models were then used to estimate the potential impact of major risk factors on the progress of a construction supply network. The simulation results for each model estimated a significant impact on the progress of the project as a whole, and these results are a strong indication of the potential for automatic detection models to have a beneficial impact on the construction materials management process, both at the site level and within the supply network.

Finally, while many approaches have been tried in studying SCs in construction, including risk effects, based on the author's best of knowledge, no study has addressed the dynamic updating of the probability of risk events throughout the construction life cycle to effectively study the impact on project time and cost. In order to reduce the impact of unseen risk factors that may affect the progress of any construction project, it is important to have tools to predict the influence of major risk factors in advance. However, risk factors keep changing in their probabilities and impacts along a project's duration, and these changes will be more severe and have more influence if recognized later rather than earlier, and will be harder and more costly to manage. Therefore, in order for better risk management, this research is aimed at helping to recognize the occurrence probabilities of risk factors during the early stages of a project.

6.1 Contributions

The main contribution of this research is developing a clear understanding of the risk events that affect supply chains and developing models that automatically detect changes in the probability distributions of risk factors in the planning and the operation phases. The research contributes to the following:

1) Identifying the life cycle phases of construction supply chains, particularly for large-scale industrial projects, and then defining and categorizing the risk factors that are applicable to each phase. Accordingly, a supply chain risk register was developed with typical probability and impact distributions in order to accommodate both risk events and uncertainty factors.

2) Introducing automated detection models for changes in the levels of risks associated with each life cycle phase of a supply chain. Two types of detection models were developed: (1) a model that combines supply chain visibility tools for collecting data automatically, such as RFID and GPS, for materials tracking (example of pipe spool manufacturing provided); (2) models that collect historical/web-based/current information to update risk events (economic and environmental).
3) Conducting simulation studies to study the impact of risk factors on activity costs and schedules using @Risk in order to propose solutions to mitigate/reduce some of the major risk factors.

6.3 Direction for Future Work

This thesis has investigated the impact of automatic detection models on risks related to construction supply networks, with a particular focus on industrial construction projects. As such, a need to continue to examine this area of research remains. A number of recommendations for areas of future research and work pertaining to automatic risk detection and the construction industry, and in continuation of this work, the following subjects are suggested for future studies:

- Increasing the level of awareness of the potential risks that influence a construction supply chain is essential if it is to be implemented successfully on a broader scale. Investigating other risk factors in order to have comprehensive details on a supply chain's progress (e.g., design delays, storage delays, etc.) is another possible means of increasing awareness.

- The ability of supply chain visibility tools to facilitate increased visibility within construction supply networks in order to examine the benefits of implementing such tools to better manage supply chain progress. This is an area in need of further examination.
- This research effort has focused on the application of automatic detection models in the industrial construction sector. Exploring the feasibility of implementing these models within other segments of the construction industry, such as residential and civil infrastructure, are other potential research areas.
- This study is limited to the construction sector and its contractors. As such, an effort should be made to facilitate and study the impact of automatic detection models on entire supply chains, from the point of materials origins through the entire construction process and point of final installation.
- Another potential research area is investigating the integration of supply chain decision support systems with project control practices in order to update projects. In addition to that is examining the integration of the detection models with BIM.
- Experimenting with the developed models with different real-life case studies and expanding the system to other fields by applying the same approach to all supply chain phases is identified to be an area in need of further research.
- Using different domains for the online data, experimenting with different automatic detection models, and examining different simulation methods is another essential research area in order to expand the model and obtain more accurate data on impacts on impact on project times and costs.
- The model can be expanded to be used as a Plugin in @Risk enable the users for a better and practical use of the model for their projects.

- Developing a commercial-level integrated prototype, experimenting with it with different case studies, and performing economic analyses of the Benefit/Cost of implementing different SCV tools.
- Some of the risk factors can be mitigated by applying some contracting strategies to reduce their impact (i.e. lock in interest rates or exchange rates).

References

1. AbouRizk, S.M. (2009). "Risk Analysis for Construction Projects: A practical guide for engineers and project managers". Edmonton: NSERC Industrial Research Chair in Construction Engineering and Management.
2. AbouRizk, H., Kostelyk, J., AbouRizk, S.M., Smid, B., & Griffith, B. (2011). "Improving Risk Analysis in the Construction Industry". CSCE Annual Conference. Ottawa, ON.
3. AbouRizk, S.M., Halpin, D.W., & Wilson, J.R. (1991). Visual Interactive Fitting of Beta Distributions. Journal of Construction Engineering and Management, 589-605.
4. Ahuja, H., Dozzi, S., & AbouRizk, S.M. (1994). *Project Management, Techniques in Planning and Controlling Construction Projects*. John Wiley and Sons, New York.
5. Ahuja, H.N., & Nandakumar, V. (1984). "Enhancing reliability of project duration forecasts". American Association of Cost Engineers Transactions, E.6.1– E.6.12.
6. Al-Bahar, J., & Crandall, K. (1990). Systematic Risk Management Approach for Construction Projects. Journal of Construction Engineering and Management, 533-546.
7. Ala-Risku, T., & Kärkkäinen, M. (2006). Material delivery problems in construction projects: a possible solution. *International Journal of Production Economics, 104*(1), 19-29.
8. Aloini, D., Dulmin, R., Mininno, V., & Ponticelli, S. (2012). Supply chain management: a review of implementation risks in the construction industry. *Business Process Management Journal, 18*(5), 735-761.

9. Angerhofer, B.J., & Angelides, M.C. (2000). "System dynamics modelling in supply chain management: research review". In Simulation Conference, 2000. Proceedings. Winter (Vol. 1, pp. 342-351). IEEE.

10. Arbulu, R., & Ballard, G. (2004, August). "Lean supply systems in construction". In The 12th Conference of the International Group for Lean Construction (IGLC12) (pp. 3-5).

11. Assaf, S.A., & Al-Hejji, S. (2006). Causes of delay in large construction projects. *International journal of project management, 24*(4), 349-357.

12. Ballard, G., and Howell, G. (1998). "What kind of production is construction?". Proc., 6th Ann. Conf. Int. Group for Lean Constr., IGLC, Guaruja, Brazil.

13. Blos, M.F., Quaddus, M., Wee, H.M., & Watanabe, K. (2009). Supply chain risk management (SCRM): a case study on the automotive and electronic industries in Brazil. *Supply Chain Management: An International Journal, 14*(4), 247-252.

14. Briscoe, G., & Dainty, A. (2005). Construction supply chain integration: an elusive goal? *Supply chain management: an international journal, 10*(4), 319-326.

15. Caridi, M., Crippa, L., Perego, A., Sianesi, A., & Tumino, A. (2010). Measuring visibility to improve supply chain performance: a quantitative approach. *Benchmarking: An International Journal, 17*(4), 593-615.

16. Chang, Y., & Makatsoris, H. (2001). Supply chain modeling using simulation. *International Journal of Simulation, 2*(1), 24-30.

17. Childerhouse, P., & Towill, D.R. (2004). Reducing uncertainty in European supply chains. *Journal of Manufacturing Technology Management, 15*(7), 585-598.

18. Construction Industry Institute (2012). *Applying Probabilistic Risk Management in Design and Construction Projects*. Austin, Texas: Construction Industry Institute.

19. Cutting-Decelle, A.F., Young, B.I., Das, B.P., Case, K., Rahimifard, S., Anumba, C.J., & Bouchlaghem, D.M. (2007). A review of approaches to supply chain communications: from manufacturing to construction. *ITcon*, 12, 73-102.

20. Chatfield, D.C. (2001). "SISCO and SCML-software tools for supply chain simulation modeling and information sharing". (PhD Dissertation, Pennsylvania State University).

21. Chen, I.J., & Paulraj, A. (2004). Understanding supply chain management: Critical research and theoretical framework. *International Journal of Production Research, 42*(1), 131-163.

22. Christopher, M., & Lee, H. (2004). Mitigating supply chain risk through improved confidence. *International journal of physical distribution & logistics management, 34*(5), 388-396.

23. Construction Industry Institute (1999). *Procurement and Materials Management: A Guide to Effective Project Execution*. University of Texas at Austin. Austin: Construction Industry Institute.

24. Cox, A., & Ireland, P. (2002). Managing construction supply chain: The common sense approach. *Engineering, Construction and Architectural Management, 9*(5-6), 409-418.

25. Davis, P.R. (2008). A relationship approach to construction supply chains. *Industrial Management & Data Systems, 108*(3), 310-327.

26. Delen, D., Hardgrave, B.C., & Sharda, R. (2007). RFID for better supply-chain management through enhanced information visibility. *Production and Operations Management, 16*(5), 613-624.

27. Ebrahimy, Y., AbouRizk, S.M., Fernando, S., & Mohamed, Y. (2011). Simulation modeling and sensitivity analysis of a tunneling construction project's supply chain. *Engineering, Construction and Architectural Management, 18*(5), 462-480.

28. Fazio, P., Moselhi, O., Théberge, P., & Revay, S. (1988). Design impact of construction fast-track. *Construction Management and Economics, 6*(3), 195-208.

29. Galway, L. (2004). Quantitative Risk Analysis for Project Management.

30. Gosling, J., Naim, M., & Towill, D. (2012). Identifying and categorizing the sources of uncertainty in construction supply chains. *Journal of Construction Engineering and Management, 139*(1), 102-110.

31. Green, S.D., Fernie, S., & Weller, S. (2005). Making sense of supply chain management: a comparative study of aerospace and construction. *Construction Management and Economics, 23*(6), 579-593.

32. Halpin, D.W., & Riggs, L.S. (1992). *Planning and Analysis of Construction Operations*. Wiley lnterscience, New York, N.Y.

33. Hegazy, T., & Menesi, W. (2012). Enhancing the critical path segments scheduling technique for project control, this paper is one of a selection of papers in this Special Issue on Construction Engineering and Management. *Canadian Journal of Civil Engineering, 39*(9), 968-977.

34. Hong-Minh, S.M., Barker, R., & Naim, M.M. (1999). “Construction supply chain trend analysis”. In Proceedings IGLC (Vol. 7, p. 85).

35. Hwamg, H.B., Chong, C.S.P., Xie, N., & Burgess, T.F. (2005). Modeling a complex supply chain: Understanding the effect of simplified assumptions. *International Journal of Production Research, 43*(13), 2829-2872.

36. Ibbs, C.W., and Crandall, K.C. (1982). Construction risk: multi-attribute approach. *Journal of Construction Division, ASCE, 108*(2), 187-200.

37. Irizarry, J., Karan, E.P., & Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in Construction*, 31, 241-254.

38. ISO (2009). *ISO Guide 73*. Switzerland: ISO.

39. Jaselskis, E.J., & El-Misalami, T. (2003). Implementing radio frequency identification in the construction process. *Journal of Construction Engineering and Management, 129*(6), 680-688.

40. Jiang, A., O'Brien, W., & Issa, R. (2005). "Construction supply chain performance management". International Conference of Computing in Civil Engineering, Cancun, Mexico,

41. Jung, J.Y., Blau, G., Pekny, J.F., Reklaitis, G.V., & Eversdyk, D. (2004). A simulation based optimization approach to supply chain management under demand uncertainty. *Computers & chemical engineering, 28*(10), 2087-2106.

42. Kang, L.S., Kim, S.K., Moon, H.S., & Kim, H.S. (2013). Development of a 4D object-based system for visualizing the risk information of construction projects. *Automation in Construction*, 31, 186-203.

43. Karim, K., Marosszeky, M., & Davis, S. (2006). Managing subcontractor supply chain for quality in construction. *Engineering, Construction and Architectural Management, 13*(1), 27-42.

44. Kei Tse, Y., Hua Tan, K., Ho Chung, S., & Kim Lim, M. (2011). Quality risk in global supply network. *Journal of Manufacturing Technology Management, 22*(8), 1002-1013.

45. Kini, D.U. (1999). Materials management: The key to successful project management. *Journal of management in engineering, 15*(1), 30-34.

46. Kiziltas, S., & Akinci, B. (2005). "The need for prompt schedule update by utilizing reality capture technologies: A case study". In *Construction Research Congress 2005: Broadening Perspectives*, pp.1-10.

47. Kumaraswamy, M.M., & Chan, D.W. (1998). Contributors to construction delays. *Construction Management & Economics, 16*(1), 17-29.

48. Lamming, R. (1993). *Beyond partnership: Strategies for innovation and lean supply*. Prentice Hall, Hemel Hempstead, UK.

49. Lee, Y.H., Cho, M.K., & Kim, Y.B. (2002). A discrete-continuous combined modeling approach for supply chain simulation. *Simulation, 78*(5), 321-329.

50. Lee, S.H., Pena-Mora, F., & Park, M. (2006). Dynamic planning and control methodology for strategic and operational construction project management. *Automation in construction, 15*(1), 84-97.

51. Li, H.X., Al-Hussein, M., Lei, Z., & Ajweh, Z. (2013). Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation. *Canadian Journal of Civil Engineering, 40*(12), 1184-1195.

52. Li, J., Tian, Y., & Yang, X. (2011). "A Supply Chain Simulation Model Based on System Dynamics". In: International Conference on Software Technology and Engineering, 3rd (ICSTE 2011). ASME Press.

53. Liu, B. (2002). *Theory and practice of uncertain programming*. Springer.

54. Love, P.E.D., Holt, G.D., Shen, L.Y., Li, H., & Irani, Z. (2002). Using systems dynamics to better understand change and rework in construction project management systems. *International Journal of Project Management,20*(6), 425-436

55. Logsdon, T. (1995). *Understand the NAVSTAR: GPS, GIS, and IVHS* (2nd Ed.). New York, NY, U.S.A.

56. Van Nostrand, R., & Futcher, K. (2001). "User survey on a WAN portfolio MIS used for portfolio/project management in Hong Kong." Proc., IT in Construction in Africa, CIB W78 Workshop, White River, South Africa, 44-1– 44-14.

57. Meng, X. (2012). The effect of relationship management on project performance in construction. *International journal of project management, 30*(2), 188-198.

58. Newhart, D.D., Statt, K.L., & Vasco, F.J. (1993). Consolidating product size to minimize inventory levels for a multi-stage production and distribution systems. *Journal of the Operational Research Society, 44*(7), 637-644.

59. Nyoman Pujawan, I., & Geraldin, L.H. (2009). House of risk: a model for proactive supply chain risk management. *Business Process Management Journal, 15*(6), 953-967.

60. Palaneeswaran, E., Kumaraswamy, M., & Thomas, S. (2003). Formulating a framework for relationally integrated construction supply chain. *Journal of Construction Research, 4*(2), 189-205.

61. Pan, N.H., Lee, M.L., & Chen, S.Q. (2011). Construction material supply chain process analysis and optimization. *Journal of Civil Engineering and Management, 17*(3), 357-370.

62. Pedrycz, W. (1998). *An introduction to fuzzy sets, analysis, and design*. Cambridge, Mass, MIT Press.

63. Peña-Mora, F., & Li, M. (2001). Dynamic planning and control methodology for design/build fast-track construction projects. *Journal of construction engineering and management, 127*(1), 1-17.

64. Phillips, H.C., Bogus, S.M., & Ross, T.J. (2009). "An Approach to Classifying Uncertainties in Construction Schedules". In *Construction Research Congress 2009@ Building a Sustainable Future* (pp.876-885). ASCE.

65. Project Management Institute (2000). *A Guide to the Project Management Body of Knowledge*. Pennsylvania: Project Management Institute.

66. Raychaudhuri, S. (2008). Introduction to Monte Carlo simulation. In *Simulation Conference, 2008. WSC 2008. Winter*, 91-100. IEEE.

67. Razavi, S.N., Young, D.A., Nasir, H., Haas, C.T., Caldas, C., Goodrum, P., et al. (2008). "Field Trial of Automated Material Tracking in Construction". CSCE 2008 Annual Conference, Quebec City, Canada.

68. Ross, T, Kreinovich, V., & Joslyn, C. (2001). "Assessing the Predictive Accuracy of Complex Simulation Models". Joint 9th IFSA World Congress and 20th NAFIPS International Conference, Vancouver, BC, IEEE Publications, 2008-2012.

69. Sarmah, S.P., Acharya, D., & Goyal, S.K. (2005). Buyer vendor coordination models in supply chain management. *European Journal of Operational Research,*

70. Song, J., Haas, C.T., Caldas, C., Ergen, E., & Akinci, B. (2006). Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects. *Automation in Construction, 15*(2), 166-177.

71. Terzi, S., & Cavalieri, S. (2004). Simulation in the supply chain context: A survey. *Computers in Industry, 53*(1), 3-16.

72. Thomas, H.R., Riley, D.R., & Messner, J.I. (2005). Fundamental principles of site material management. *Journal of Construction Engineering and Management, 131*(7), 808-815.

73. Tiger, A.A., & Simpson, P. (2003). Using discrete event simulation to create flexibility in APAC supply chain management. *Global Journal of Flexible Systems Management, 4*(4), 15.

74. Tommelein, I.D., Akel, N., & Boyers, J.C. (2003). "Capital projects supply chain management: SC tactics of a supplier organization". Construction Research Congress in Construction, Honolulu, Hawaii,

75. Tommelein, I. D., & Weissenberger, M. (1999). "More just-in-time: Location of buffers in structural steel supply and construction processes". Proc., 7th Ann. Conf. Intl. Group for Lean Constr., IGLC, Berkeley, CA, 109-120.

76. Tse, Y.K., & Tan, K.H. (2012). Managing product quality risk and visibility in multi-layer supply chain. *International journal of production economics, 139*(1), 49-57.

77. Vaidyanathan, K., & O'Brien, W. (2005). Opportunities for IT to support the construction supply chain. Cancun, Mexico,

78. Vidalakis, C., Tookey, J. E., & Sommerville, J. (2011). Logistics simulation modelling across construction supply chains. *Construction Innovation, 11*(2), 212-228.

79. Vilko, J. P., & Hallikas, J. M. (2012). Risk assessment in multimodal supply chains. *International Journal of Production Economics, 140*(2), 586-595.

80. Vlachos, D., Georgiadis, P., & Iakovou, E. (2007). A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains. *Computers & Operations Research, 34*(2), 367-394.

81. Vrijhoef, R., & Koskela, L. (1999). “Roles of supply chain management in construction”. Retrieved from: http://wvvrvv.ce.berkelev.edu/~tommelein/IGLC-7/PDF/Vriihoef&Koskela.pdf

82. Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *Eur. J. Purchasing & Supply Manage, 6*(3-4), 169-178.

83. Walsh, K., Hershauer, J., Tommelein, I., & Walsh, T. (2004). Strategic positioning of inventory to match demand in a capital projects supply chain. *Journal of Construction Engineering and Management, 130*(6), 818-826.

84. Womack, J.P., Jones, D.T., & Roos, D. (1990). *The machine that changed the world: The story of lean production—Toyota's secret weapon in the global car wars that is now revolutionizing world industry*. Free Press, New York.

85. Wong, A. (1999). Total quality management in the construction industry in Hong Kong: a supply chain management perspective. *Total Quality Management & Business Excellence 10*(2), 199-208.

86. Young, D.A., Haas, C.T., Goodrum, P., & Caldas, C. (2011). Improving construction supply network visibility by using automated materials locating and tracking technology. *Journal of Construction Engineering and Management, 137*(11), 976-984.

Appendix A (VBA Code for Environmental and Economic Factors)

```
'Define which columns of the spreadsheet for each value

Public Const COL_DATE = 1

Public Const COL_MAX = 2

Public Const COL_MIN = 3

Public Const COL_WIND_SPEED = 4

Public Const COL_WIND_DIR_CODE = 5

Public Const COL_PRECIP_VAL = 6

Public Const COL_PRESSURE = 7

Public Const COL_TEMP_MORN = 9

Public Const COL_TEMP_DAY = 10

Public Const COL_TEMP_EVE = 11

Public Const COL_TEMP_NIGHT = 12

Public Const COL_CONDITIONS = 13

Public Const COL_SYMBOL = 14

Public Const COL_PRECIP_TYPE = 15

Public Const COL_WIND_DIR_DEG = 16

Public Const COL_WIND_DIR_NAME_ = 17

Public Const COL_WIND_SPEED_NAME = 18

Public Const COL_PRESSURE_UNIT = 19




Sub Import_OpenWeatherMap()
```

```
Dim ws As Worksheet: Set ws = ActiveSheet
    Range("B6:Y21").ClearContents
    ' Get teh city name, default to Waterloo
Dim theCity As String
theCity = ws.Range("cityname").Cells(1, 1).Value
If (Len(Trim(theCity)) = 0) Or (theCity = "the city") Then
    theCity = "Waterloo, Ontario"
End If
' MsgBox theCity


' build the command to send to openweathermap
Dim req As New XMLHTTP60
Dim cmdstr As String
cmdstr = "http://api.openweathermap.org/data/2.5/forecast/daily?q=" + theCity + "&mode=xml&units=metric&cnt=7&apiid=0f7fc904d5a58365fe2e3924277d90d6"
cmdstr = "http://api.openweathermap.org/data/2.5/forecast/daily?q=" + theCity + "&mode=xml&units=metric&cnt=16&appid=0f7fc904d5a58365fe2e3924277d90d6"


'MsgBox cmdstr
req.Open "get", cmdstr, False
req.send
If (InStr(req.responseText, "Invalid API key")) Then
    ws.Range("openweathermap").Cells(3, COL_DATE + 2).Value = cmdstr
    ws.Range("openweathermap").Cells(3, COL_DATE + 3).Value = req.responseText
End If
' load the result into a document structure
```

```
  Dim resp As New DOMDocument60

  resp.LoadXML req.responseText

  Dim weather, Location As IXMLDOMNode

      Dim xmlAttributes As MSXML2.IXMLDOMNamedNodeMap

    Dim xmlName As MSXML2.IXMLDOMNode

    ' use i to count through the rows of the spreadsheet, one for each day

  Dim i As Integer

  i = 1

    For Each Location In resp.getElementsByTagName("location")

    If (Location.HasChildNodes) Then

      ws.Range("openweathermap").Cells(0, 1).Value = (Location.ChildNodes.Item(0).Text) + ",
" + (Location.ChildNodes.Item(2).Text)

    End If

  Next Location

    ' repeat this block for every day that is returnd

  For Each weather In resp.getElementsByTagName("time")

    Dim symbolurl As String

    Dim symbol As Shape

    i = i + 1

        ' the date

    Set xmlAttributes = weather.Attributes

    ws.Range("openweathermap").Cells(i,                    COL_DATE).Value                    =
xmlAttributes.getNamedItem("day").Text



    ' symbol:  number, name, var
```

```
Set xmlAttributes = weather.SelectNodes("symbol")(0).Attributes

ws.Range("openweathermap").Cells(i, COL_CONDITIONS).Value = xmlAttributes.getNamedItem("name").Text

symbolurl = "http://openweathermap.org/img/w/" + xmlAttributes.getNamedItem("var").Text + ".png"

Dim thiscell As Range

Set thiscell = ws.Range("openweathermap").Cells(i, COL_SYMBOL)

Set symbol = ws.Shapes.AddShape(msoShapeRectangle, thiscell.Left, thiscell.Top, thiscell.Width, thiscell.Height)

symbol.Fill.UserPicture symbolurl



' temperature values, converted from Kelvin to Celsius

Set xmlAttributes = weather.SelectNodes("temperature")(0).Attributes

ws.Range("openweathermap").Cells(i, COL_MIN).Value = ToCelsius(xmlAttributes.getNamedItem("min").Text)

ws.Range("openweathermap").Cells(i, COL_MAX).Value = ToCelsius(xmlAttributes.getNamedItem("max").Text)

ws.Range("openweathermap").Cells(i, COL_TEMP_DAY).Value = ToCelsius(xmlAttributes.getNamedItem("day").Text)

ws.Range("openweathermap").Cells(i, COL_TEMP_NIGHT).Value = ToCelsius(xmlAttributes.getNamedItem("night").Text)

ws.Range("openweathermap").Cells(i, COL_TEMP_EVE).Value = ToCelsius(xmlAttributes.getNamedItem("eve").Text)

ws.Range("openweathermap").Cells(i, COL_TEMP_MORN).Value = ToCelsius(xmlAttributes.getNamedItem("morn").Text)



'precipitation: value, type

Set xmlAttributes = weather.SelectNodes("precipitation")(0).Attributes

If (xmlAttributes.Length > 0) Then
```

```
        ws.Range("openweathermap").Cells(i,            COL_PRECIP_VAL).Value            =
xmlAttributes.getNamedItem("value").Text

        ws.Range("openweathermap").Cells(i,            COL_PRECIP_TYPE).Value            =
xmlAttributes.getNamedItem("type").Text

    End If



    ' windDirection: deg, code, name

     Set xmlAttributes = weather.SelectNodes("windDirection")(0).Attributes

    If (xmlAttributes.Length > 0) Then

        ws.Range("openweathermap").Cells(i,          COL_WIND_DIR_DEG).Value          =
xmlAttributes.getNamedItem("deg").Text

        ws.Range("openweathermap").Cells(i,          COL_WIND_DIR_CODE).Value          =
xmlAttributes.getNamedItem("code").Text

        ws.Range("openweathermap").Cells(i,          COL_WIND_DIR_NAME_).Value          =
xmlAttributes.getNamedItem("name").Text

    End If



    ' windSpeed: mps, name

     Set xmlAttributes = weather.SelectNodes("windSpeed")(0).Attributes

    If (xmlAttributes.Length > 0) Then

        ws.Range("openweathermap").Cells(i,            COL_WIND_SPEED).Value            =
xmlAttributes.getNamedItem("mps").Text

        ws.Range("openweathermap").Cells(i,        COL_WIND_SPEED_NAME).Value        =
xmlAttributes.getNamedItem("name").Text

    End If




    ' pressure: unit, value
```

```
 Set xmlAttributes = weather.SelectNodes("pressure")(0).Attributes
If (xmlAttributes.Length > 0) Then
    ws.Range("openweathermap").Cells(i, COL_PRESSURE_UNIT).Value = xmlAttributes.getNamedItem("unit").Text
    ws.Range("openweathermap").Cells(i, COL_PRESSURE).Value = xmlAttributes.getNamedItem("value").Text
End If


' humidity: value, unit
 Set xmlAttributes = weather.SelectNodes("humidity")(0).Attributes
If (xmlAttributes.Length > 0) Then
    ws.Range("openweathermap").Cells(i, 20).Value = xmlAttributes.getNamedItem("value").Text
    ws.Range("openweathermap").Cells(i, 21).Value = xmlAttributes.getNamedItem("unit").Text
End If


' clouds: value, all, unit
 Set xmlAttributes = weather.SelectNodes("clouds")(0).Attributes
If (xmlAttributes.Length > 0) Then
    ws.Range("openweathermap").Cells(i, 22).Value = xmlAttributes.getNamedItem("value").Text
    ws.Range("openweathermap").Cells(i, 23).Value = xmlAttributes.getNamedItem("all").Text
    ws.Range("openweathermap").Cells(i, 24).Value = xmlAttributes.getNamedItem("unit").Text
End If
Function ToCelsius(degreesKelvin As Double) As Double
```

```
' Kelvin (subtract 273.15 to convert to Celsius)

ToCelsius = degreesKelvin - 273.15

End Function

'http://www.mrexcel.com/forum/excel-questions/640780-parse-json-excel-visual-basic-applications.html

' max 59 days ago

Function Get_startdate() As String

  Dim thetime, startdate As Date

  thetime = Now()

  startdate = DateAdd("d", -58, thetime)

  Get_startdate = "&date=" + Format(startdate, "yyyy-M-dd")

End Function


' today

Function Get_enddate() As String

  Dim thetime As Date

  thetime = Now()

  Get_enddate = "&enddate=" + Format(thetime, "yyyy-M-dd")

End Function


Function get_wwokey() As String

  Dim ws As Worksheet: Set ws = Worksheets("keys")

  Dim thekey As String

  thekey = ws.Range("wwonewkey").Cells(1, 1).Value

  If (Len(Trim(thekey)) = 0) Then
```

```
    thekey = "71b21cb0a11c0bcce35eb373cdbcf"
  End If
  get_wwokey = "&key=" + thekey
End Function

Function Get_City() As String
  Dim ws As Worksheet: Set ws = ActiveSheet
  ' Get teh city name, default to Waterloo
  Dim theCity As String
  theCity = ws.Range("cityname").Cells(1, 1).Value
  If (Len(Trim(theCity)) = 0) Or (theCity = "the city") Then
    theCity = "Waterloo, Ontario"
  End If
'   MsgBox theCity
  Get_City = "q=" + theCity
End Function

Sub Import_HistoricalData()
  Dim ws As Worksheet: Set ws = ActiveSheet
    ' openweathermap
  ' openweathermap does not provide historic data in free account
'   Dim req As New XMLHTTP60
  'req.Open "get",
"http://api.openweathermap.org/data/2.5/history/city?q=waterloo,ontario&mode=xml&APIID=d
c4f8b49b3ec4facf0fdf1a684acf164", False
'req.Open"get",
```

```
"http://api.openweathermap.org/data/2.5/history/city?id=2885679&type=hour&APIID=dc4f8b49b3ec4facf0fdf1a684acf164", False

   'req.send

   'MsgBox req.responseText



   ' World Weather Online

   ' max 60 days back

   Dim req As New XMLHTTP60

   req.Open "get", "http://api.worldweatheronline.com/free/v2/past-weather.ashx?" + Get_City() + "&format=xml" + Get_startdate() + Get_enddate() + "&includelocation=yes&show_comments=no&tp=24" + get_wwokey(), False

   req.send

   ' MsgBox req.responseText



   ' load the result into a document structure

   Show_WorldWeatherOnline_Results (req.responseText)

   End Sub



Sub Show_WorldWeatherOnline_Results(responseText As String)

    Dim ws As Worksheet: Set ws = ActiveSheet

    Dim i As Integer

    Range("g6:Y90").ClearContents

     ' load the result into a document structure

   Dim resp As New DOMDocument60

   resp.LoadXML responseText

   Dim weather, Location As IXMLDOMNode
```

```
  'ws.Range("historicresults").Cells(3, COL_DATE + 3).Value = resp.XML
  For i = 1 To 9
    ws.Range("historicresults").Cells(0, i).Interior.Color = RGB(109, 105, 42)
    ws.Range("historicresults").Cells(0, i).Font.Color = vbWhite
    ws.Range("historicresults").Cells(0, i).Font.Bold = True
    ws.Range("historicresults").Cells(0, i).Font.Size = 14
    ws.Range("historicresults").Cells(1, i).Interior.Color = RGB(109, 105, 42)
    ws.Range("historicresults").Cells(1, i).Font.Color = vbWhite
    ws.Range("historicresults").Cells(1, i).Font.Bold = True
    ws.Range("historicresults").Cells(1, i).Font.Size = 14
Next i
  For Each Location In resp.getElementsByTagName("query")
  If (Location.HasChildNodes) Then
    ws.Range("historicresults").Cells(0, 1).Value = (Location.ChildNodes.Item(0).Text)
  End If
Next Location
  ' headings
ws.Range("historicresults").Cells(1, 1).Value = "Date"
ws.Range("historicresults").Cells(1, 2).Value = "Sunrise"
ws.Range("historicresults").Cells(1, 3).Value = "Sunset"
ws.Range("historicresults").Cells(1, 4).Value = "Max temp"
ws.Range("historicresults").Cells(1, 5).Value = "Min temp"
ws.Range("historicresults").Cells(1, 6).Value = "Wind Speed"
ws.Range("historicresults").Cells(1, 7).Value = "Precipitation"
ws.Range("historicresults").Cells(1, 8).Value = "Visibility"
```

```
ws.Range("historicresults").Cells(1, 9).Value = "Cloud Cover"
i = 1
  For Each weather In resp.getElementsByTagName("weather")
  i = i + 1
    ' the date
  Set xmlAttributes = weather.Attributes
  For Each element In weather.getElementsByTagName("date")
    ws.Range("historicresults").Cells(i, 1).Value = element.ChildNodes.Item(0).Text
  Next element
  For Each element In weather.getElementsByTagName("sunrise")
    ws.Range("historicresults").Cells(i, 2).Value = element.ChildNodes.Item(0).Text
  Next element
  For Each element In weather.getElementsByTagName("sunset")
    ws.Range("historicresults").Cells(i, 3).Value = element.ChildNodes.Item(0).Text
  Next element
  For Each element In weather.getElementsByTagName("maxtempC")
    ws.Range("historicresults").Cells(i, 4).Value = element.ChildNodes.Item(0).Text
  Next element
  For Each element In weather.getElementsByTagName("mintempC")
    ws.Range("historicresults").Cells(i, 5).Value = element.ChildNodes.Item(0).Text
  Next element
  For Each element In weather.getElementsByTagName("windspeedKmph")
    ws.Range("historicresults").Cells(i, 6).Value = element.ChildNodes.Item(0).Text
  Next element
  For Each element In weather.getElementsByTagName("precipMM")
```

```
      ws.Range("historicresults").Cells(i, 7).Value = element.ChildNodes.Item(0).Text
    Next element
    For Each element In weather.getElementsByTagName("visibility")
      ws.Range("historicresults").Cells(i, 8).Value = element.ChildNodes.Item(0).Text
    Next element
    For Each element In weather.getElementsByTagName("cloudcover")
      ws.Range("historicresults").Cells(i, 9).Value = element.ChildNodes.Item(0).Text
    Next element
       Next weather
  End Sub


Sub Import_HistoricalData_RawFromStation()
' http://api.openweathermap.org/data/2.5/history/station?id=5091&type=tick
  Dim ws As Worksheet: Set ws = ActiveSheet
  ' build the command to send to openweathermap
  Dim req As New XMLHTTP60
  req.Open "get",
"http://api.openweathermap.org/data/2.5/history/station?id=5091&type=tick&mode=xml&APII
D=0f7fc904d5a58365fe2e3924277d90d6", False
  req.send
  MsgBox req.responseText
  End Sub


Sub Import_HistoricalData_GroupedByHour()
  Dim ws As Worksheet: Set ws = ActiveSheet
  ' build the command to send to openweathermap
```

```
  Dim req As New XMLHTTP60

  req.Open "get", "http://api.openweathermap.org/data/2.5/history/station?id=5091&type=hour&mode=xml&APIID=0f7fc904d5a58365fe2e3924277d90d6", False

  req.send

  MsgBox req.responseText

  End Sub


Sub Import_HistoricalData_GroupedByDay()

' Historical data grouped by days

  Dim ws As Worksheet: Set ws = ActiveSheet

  ' build the command to send to openweathermap

  Dim req As New XMLHTTP60

  req.Open "get", "http://api.openweathermap.org/data/2.5/history/station?id=5091&type=day&mode=xml&APIID=0f7fc904d5a58365fe2e3924277d90d6", False

  req.send

  MsgBox req.responseText

  End Sub

Sub Import_InterestHistory()

  Dim ws As Worksheet: Set ws = ActiveSheet

  Dim colnum As Integer

  Dim dataset As String

  Dim title As String

    Sheet1.txtCountryCode.Text = UCase(Sheet1.txtCountryCode.Text)

    dataset = Sheet1.txtCountryCode.Text + "_FR_INR_LEND"
```

```
  colnum = 1
  title = "Lending Rates History"
  gethistoricrates dataset, colnum, title
    dataset = Sheet1.txtCountryCode.Text + "_FR_INR_DPST"
  colnum = 4
  title = "Deposit Rates History"
  gethistoricrates dataset, colnum, title
    dataset = Sheet1.txtCountryCode.Text + "_FR_INR_RINR"
  colnum = 7
  title = "Real Rates History"
  gethistoricrates dataset, colnum, title
  End Sub

Sub Import_InterestRates()
  Dim ws As Worksheet: Set ws = ActiveSheet
  Dim prevcode As String: prevcode = ""
  Dim rownum As Long
    Range("B6:F400").Clear
  rownum = 1
     ' Get The list of available rates:
 ' https://www.quandl.com/api/v3/databases/WORLDBANK/codes.csv
 ' sort by first column
 ' find unique three letter codes in first column, add FR_INR_LEND or FR_INR_DPST or
FR_INR_RINR
 ' use description column to get the country name
```

```
 ' send a request for each code, only return first value
 ' make a row
 ' shortcut:  the list of codes is a sheet in this spreadsheet, don't need to call codes.csv
  Dim codelist As Range
  Dim row As Range
  Dim cell As Range
      Set codelist = ThisWorkbook.Sheets("WORLDBANK-datasets-codes").UsedRange
      For Each row In codelist.rows
     Dim datasetname, prefix As String
     Dim CountryCode As String
     Dim countryname As String
     datasetname = row.Cells(1).Value
     prefix = Left(datasetname, 13)


     ' skip over some useless ones (cellphones, life expectancy)
     If (StrComp(prefix, "WORLDBANK/CEL", vbTextCompare) And StrComp(prefix, "WORLDBANK/LIF", vbTextCompare)) Then
If (StrComp(prefix, prevcode, vbTextCompare) And StrComp(prefix, "CEL", vbTextCompare)) Then
            CountryCode = Right(prefix, 3)
            countryname = Left(row.Cells(2).Value, InStr(row.Cells(2).Value, ":") - 1)
            ws.Range("interestrates").Cells(rownum, 1) = CountryCode
            ws.Range("interestrates").Cells(rownum, 2) = countryname
            ' MsgBox GetRecentRate(countrycode + "_FR_INR_LEND")
            ws.Range("interestrates").Cells(rownum, 3) = GetRecentRate(CountryCode + "_FR_INR_LEND")
```

```
        ws.Range("interestrates").Cells(rownum, 4) = GetRecentRate(CountryCode +
"_FR_INR_DPST")

        ws.Range("interestrates").Cells(rownum, 5) = GetRecentRate(CountryCode +
"_FR_INR_RINR")

        ' shade alternate rows, for readibility

        If rownum Mod 2 Then

          ws.Range("interestrates").Cells(rownum, 1).Style = "20% - Accent3"

          ws.Range("interestrates").Cells(rownum, 2).Style = "20% - Accent3"

          ws.Range("interestrates").Cells(rownum, 3).Style = "20% - Accent3"

          ws.Range("interestrates").Cells(rownum, 4).Style = "20% - Accent3"

          ws.Range("interestrates").Cells(rownum, 5).Style = "20% - Accent3"

        End If

          ' and move to the next country

        prevcode = prefix

        rownum = rownum + 1

      End If

    End If

      Next row

 End Sub


Sub gethistoricrates(dataset As String, colnum As Integer, title As String)

  Dim ws As Worksheet: Set ws = ActiveSheet

  Dim therates() As String

  Dim rownum As Integer

  therates = GetRates(dataset)

    rownum = 1
```

```
  ws.Range("historyrates").Cells(rownum, colnum) = title
ws.Range("historyrates").Cells(rownum + 1, colnum + 1) = "Date"
ws.Range("historyrates").Cells(rownum + 1, colnum + 1) = "Rate"
ws.Range("historyrates").Cells(rownum, colnum).Style = "Accent6"
ws.Range("historyrates").Cells(rownum, colnum + 1).Style = "Accent6"
ws.Range("historyrates").Cells(rownum, colnum).Font.Size = 15
ws.Range("historyrates").Cells(rownum, colnum + 1).Font.Size = 15
ws.Range("historyrates").Cells(rownum + 1, colnum).Font.Size = 15
ws.Range("historyrates").Cells(rownum + 1, colnum + 1).Font.Size = 15
ws.Range("historyrates").Cells(rownum + 1, colnum).Style = "Accent6"
ws.Range("historyrates").Cells(rownum + 1, colnum + 1).Style = "Accent6"
rownum = rownum + 1
ws.Range("historyrates").Cells(rownum, colnum) = therates(1)
ws.Range("historyrates").Cells(rownum + 1, 1) = therates(2)

 Dim element As Variant
 For Each element In therates
    Dim mycells() As String
    If Len(element) > 1 Then
        mycells = Split(element, ",")
        ws.Range("historyrates").Cells(rownum, colnum) = mycells(0)
        ws.Range("historyrates").Cells(rownum, colnum + 1) = mycells(1)
        rownum = rownum + 1
    End If
    Next element
```

```
    ' shade alternate rows, for readibility
   If rownum Mod 2 Then
     ws.Range("interestrates").Cells(rownum, colnum).Style = "20% - Accent3"
     ws.Range("interestrates").Cells(rownum, colnum + 1).Style = "20% - Accent3"
   End If
  End Sub
Function GetRates(dataset As String) As String()
   Dim myURL As String
   Dim retval() As String
   myURL = "https://www.quandl.com/api/v3/datasets/WORLDBANK/" + dataset + ".csv?api_key=vix44PAozq3QErUHPeV4"
      Dim WinHttpReq As Object
   Set WinHttpReq = CreateObject("Microsoft.XMLHTTP")
   WinHttpReq.Open "GET", myURL, False
   WinHttpReq.send
   retval = Split("", vbLf)
    ' MsgBox WinHttpReq.responseText
      myURL = WinHttpReq.responseBody
   If WinHttpReq.Status = 200 Then
     Dim pos As Integer
     Dim therates As String
     therates = WinHttpReq.responseText
     ' first row has two values: column headings
     ' second row contains date, then the value we want.
      retval = Split(therates, vbLf)
```

```
    End If
    GetRates = retval
    End Function
Function GetRecentRate(dataset As String) As String
    Dim TextLines() As String
    Dim retval As String
    retval = ""
        TextLines = GetRates(dataset)
        If UBound(TextLines) > 1 Then
        ' MsgBox Right(TextLines(1), (Len(TextLines(1)) - InStr(TextLines(1), ",")))
            retval = Right(TextLines(1), (Len(TextLines(1)) - InStr(TextLines(1), ",")))
        Else
            retval = ""
        End If
GetRecentRate = retval
    End Function
```

Appendix B (Interest Rates at Time of Writing)

Code	Country	Lend Rate	Deposit Rate	Real Rate
ABW	Aruba	8.233	2.175	16.759
AGO	Angola	16.382	3.859	12.189
ALB	Albania	8.659	1.915	7.160
ARE	United Arab Emirates	8.053	3.603	10.652
ARG	Argentina	24.009	20.418	-3.302
ARM	Armenia	16.409	10.426	13.638
ATG	Antigua and Barbuda	10.072	2.893	7.483
AUS	Australia	5.950	2.904	4.279
AUT	Austria	5.638	2.206	5.348
AZE	Azerbaijan	17.858	9.172	17.627
BDI	Burundi	15.668	4.000	6.800
BEL	Belgium	9.500	1.648	8.268
BEN	Benin	16.750	3.500	13.322
BFA	Burkina Faso	16.750	3.500	16.486
BGD	Bangladesh	13.000	9.077	6.420
BGR	Bulgaria	8.278	1.656	7.601
BHR	Bahrain	5.868	0.982	7.466
BHS	Bahamas, The	4.750	1.418	4.842
BIH	Bosnia and Herzegovina	6.638	2.666	4.987
BLR	Belarus	18.742	18.583	0.584
BLZ	Belize	10.822	3.585	9.755
BOL	Bolivia	9.694	1.739	3.524
BRA	Brazil	32.008	10.024	23.491
BRB	Barbados	8.383	2.509	6.935
BRN	Brunei Darussalam	5.500	0.300	2.417
BTN	Bhutan	14.150	4.000	9.117
BWA	Botswana	9.000	2.534	0.883
CAF	Central African Republic	15.000	2.600	17.732
CAN	Canada	3.000	0.550	1.201
CHE	Switzerland	2.690	0.020	2.887
CHL	Chile	8.098	3.919	2.545
CHN	China	5.600	2.750	4.734
CIV	Cote d'Ivoire	16.750	3.500	16.778
CMR	Cameroon	15.000	2.600	13.835
COD	Congo, Dem. Rep.	18.693	4.007	17.165
COG	Congo, Rep.	15.000	2.600	13.724

COL	Colombia	10.867	4.089	8.879
COM	Comoros	10.500	1.750	8.631
CPV	Cape Verde	10.898	3.482	11.823
CRI	Costa Rica	14.903	3.323	9.707
CYP	Cyprus	6.741	3.439	2.014
CZE	Czech Republic	4.645	0.701	2.229
DEU	Germany	9.698	2.653	8.150
DJI	Djibouti	12.690	1.238	9.478
DMA	Dominica	8.937	2.875	7.202
DNK	Denmark	7.100	2.400	4.643
DOM	Dominican Republic	13.903	6.727	12.275
DZA	Algeria	8.000	1.750	8.732
ECU	Ecuador	14.930	4.028	7.763
EGY	Egypt, Arab Rep.	11.708	6.917	0.204
ESP	Spain	4.306	2.500	0.183
EST	Estonia	4.764	0.507	2.638
ETH	Ethiopia	8.000	4.675	-17.122
FIN	Finland	3.689	1.025	3.063
FJI	Fiji	5.761	1.859	2.457
FRA	France	6.600	1.146	4.874
FSM	Micronesia, Fed. Sts.	15.833	0.539	13.688
GAB	Gabon	15.000	2.600	9.259
GBR	United Kingdom	0.500	4.483	-1.243
GEO	Georgia	11.910	8.426	7.846
GHA	Ghana	25.583	12.904	-5.862
GIN	Guinea	19.375	14.350	12.300
GMB	Gambia, The	28.500	16.511	22.019
GNB	Guinea-Bissau	51.750	3.500	8.989
GNQ	Equatorial Guinea	15.000	2.600	12.460
GRC	Greece	6.786	2.229	3.481
GRD	Grenada	9.186	2.400	4.976
GTM	Guatemala	13.773	5.478	10.503
GUY	Guyana	12.833	1.073	7.949
HKG	Hong Kong SAR, China	5.000	0.010	2.045
HND	Honduras	20.612	10.823	14.736
HRV	Croatia	9.247	1.521	8.326
HTI	Haiti	10.773	2.614	6.711
HUN	Hungary	4.435	1.421	1.294
IDN	Indonesia	11.658	8.753	6.844
IRL	Ireland	2.648	0.010	-0.302

IRN	Iran, Islamic Rep.	11.000	16.942	-2.388
IRQ	Iraq	13.126	5.747	14.978
ISL	Iceland	7.743	4.846	3.567
ISR	Israel	3.907	0.798	2.918
ITA	Italy	4.867	0.945	3.981
JAM	Jamaica	17.217	5.267	8.731
JOR	Jordan	8.990	4.519	5.361
JPN	Japan	1.219	0.415	-0.416
KEN	Kenya	17.313	8.373	8.363
KGZ	Kyrgyz Republic	15.500	9.843	7.016
KNA	St. Kitts and Nevis	9.282	3.184	7.945
KOR	Korea, Rep.	4.263	2.536	3.680
KSV	Kosovo	9.239	1.105	8.807
KWT	Kuwait	4.561	2.021	3.679
LAO	Lao PDR	22.613	3.000	11.447
LBN	Lebanon	7.274	5.913	6.121
LBR	Liberia	13.489	3.872	9.916
LBY	Libya	6.000	2.500	28.212
LCA	St. Lucia	8.998	2.800	4.929
LKA	Sri Lanka	7.838	7.498	2.642
LSO	Lesotho	10.339	2.725	2.971
LTU	Lithuania	5.989	1.710	3.603
LUX	Luxembourg	5.271	3.313	5.705
LVA	Latvia	5.923	0.128	4.510
MAC	Macao SAR, China	5.250	0.050	-3.009
MAR	Morocco	11.500	3.893	9.889
MDA	Moldova	11.013	5.717	4.672
MDG	Madagascar	60.000	12.400	50.862
MDV	Maldives	11.417	4.139	6.820
MEX	Mexico	3.552	0.840	-0.011
MKD	Macedonia, FYR	7.457	3.699	5.932
MLI	Mali	16.750	3.500	14.493
MLT	Malta	4.703	3.033	2.466
MMR	Myanmar	13.000	8.000	11.078
MNE	Montenegro	9.413	2.139	6.988
MNG	Mongolia	19.025	12.315	12.321
MOZ	Mozambique	14.798	8.578	11.647
MRT	Mauritania	17.000	5.810	24.245
MUS	Mauritius	8.500	6.784	6.550
MWI	Malawi	44.290	13.175	19.297

MYS	Malaysia	4.587	3.048	2.266
NAM	Namibia	8.699	4.248	-2.709
NER	Niger	16.750	3.500	15.480
NGA	Nigeria	16.548	9.339	11.356
NIC	Nicaragua	13.538	1.048	4.059
NLD	Netherlands	1.625	2.737	0.370
NOR	Norway	4.280	2.280	10.221
NPL	Nepal	8.000	3.625	-6.207
NZL	New Zealand	5.804	4.108	1.364
OMN	Oman	5.083	2.017	6.954
PAK	Pakistan	11.730	7.265	4.271
PAN	Panama	6.830	2.159	4.665
PER	Peru	15.743	2.312	12.465
PHL	Philippines	5.767	1.229	2.336
PNG	Papua New Guinea	9.376	0.332	7.745
POL	Poland	5.484	2.200	3.573
PRT	Portugal	5.189	2.400	1.830
PRY	Paraguay	21.186	4.307	14.195
QAT	Qatar	4.964	1.352	6.908
ROU	Romania	8.466	3.020	4.487
RUS	Russian Federation	11.143	6.041	3.683
RWA	Rwanda	16.670	7.100	13.672
SEN	Senegal	16.750	3.500	17.845
SGP	Singapore	5.350	0.144	5.120
SLB	Solomon Islands	10.910	0.246	1.985
SLE	Sierra Leone	19.412	6.606	23.235
SLV	El Salvador	13.958	9.314	10.478
SMR	San Marino	5.920	1.083	4.516
SRB	Serbia	14.810	6.810	12.682
STP	Sao Tome and Principe	23.280	3.385	12.311
SUR	Suriname	12.283	7.092	8.995
SVK	Slovak Republic	5.762	3.759	2.848
SVN	Slovenia	5.949	1.404	2.509
SWE	Sweden	3.314	0.789	2.490
SWZ	Swaziland	8.625	2.140	2.802
SYC	Seychelles	11.648	2.333	-3.938
SYR	Syrian Arab Republic	9.901	6.216	3.422
TCD	Chad	15.000	2.600	11.324
TGO	Togo	17.500	3.500	13.806
THA	Thailand	6.958	1.958	5.384

TJK	Tajikistan	24.531	5.490	18.080
TLS	Timor-Leste	12.866	0.853	13.863
TON	Tonga	8.950	2.837	9.288
TTO	Trinidad and Tobago	7.500	1.500	3.606
TUN	Tunisia	4.815	7.366	-3.689
TZA	Tanzania	16.203	9.855	11.014
UGA	Uganda	21.528	10.810	18.649
UKR	Ukraine	17.718	12.100	2.603
URY	Uruguay	15.534	4.898	5.454
USA	United States	3.250		1.736
VCT	St. Vincent and the Grenadines	9.031	2.633	7.076
VEN	Venezuela, RB	17.212	14.682	-21.140
VNM	Vietnam	8.665	7.140	4.826
VUT	Vanuatu	4.692	1.104	2.282
WSM	Samoa	9.981	3.020	9.657
YEM	Yemen, Rep.	22.083	15.250	13.151
ZAF	South Africa	9.125	5.801	2.505
ZMB	Zambia	11.573	7.877	2.778
ZWE	Zimbabwe	578.958	121.500	572.936

Appendix C (Historical Interest Rates for Canada)

Date	Lending Rates Value	Date	Deposit Rates Value	Date	Real Rates Value
2013-12-31	3.000	2013-12-31	0.550	2013-12-31	1.594
2012-12-31	3.000	2012-12-31	0.483	2012-12-31	1.471
2011-12-31	3.000	2011-12-31	0.475	2011-12-31	-0.377
2010-12-31	2.604	2010-12-31	0.200	2010-12-31	-0.042
2009-12-31	2.396	2009-12-31	0.096	2009-12-31	4.640
2008-12-31	4.729	2008-12-31	1.500	2008-12-31	0.805
2007-12-31	6.104	2007-12-31	2.083	2007-12-31	2.776
2006-12-31	5.813	2006-12-31	1.825	2006-12-31	3.021
2005-12-31	4.417	2005-12-31	0.792	2005-12-31	1.170
2004-12-31	4.000	2004-12-31	0.783	2004-12-31	0.698
2003-12-31	4.688	2003-12-31	1.100	2003-12-31	1.309
2002-12-31	4.208	2002-12-31	0.829	2002-12-31	2.945
2001-12-31	5.813	2001-12-31	2.254	2001-12-31	4.123
2000-12-31	7.271	2000-12-31	3.483	2000-12-31	2.876
1999-12-31	6.438	1999-12-31	2.879	1999-12-31	4.493
1998-12-31	6.604	1998-12-31	3.079	1998-12-31	6.826
1997-12-31	4.958	1997-12-31	1.903	1997-12-31	3.774
1996-12-31	6.063	1996-12-31	3.003	1996-12-31	4.232
1995-12-31	8.646	1995-12-31	5.283	1995-12-31	6.267
1994-12-31	6.875	1994-12-31	3.981	1994-12-31	5.351
1993-12-31	5.938	1993-12-31	3.208	1993-12-31	4.554
1992-12-31	7.479	1992-12-31	3.917	1992-12-31	5.901
1991-12-31	9.938	1991-12-31	5.750	1991-12-31	6.662
1990-12-31	14.063	1990-12-31	9.854	1990-12-31	10.338
1989-12-31	13.333	1989-12-31	9.083	1989-12-31	8.273
1988-12-31	10.833	1988-12-31	6.646	1988-12-31	6.042
1987-12-31	9.521	1987-12-31	5.688	1987-12-31	4.552
1986-12-31	10.521	1986-12-31	7.083	1986-12-31	7.249
1985-12-31	10.583	1985-12-31	7.792	1985-12-31	7.046
1984-12-31	12.063	1984-12-31	8.938	1984-12-31	8.262
1983-12-31	11.167	1983-12-31	7.333	1983-12-31	5.129
1982-12-31	15.813	1982-12-31	12.917	1982-12-31	6.464
1981-12-31	19.292	1981-12-31	15.958	1981-12-31	7.687
1980-12-31	14.250	1980-12-31	11.521	1980-12-31	3.796
1979-12-31	12.896	1979-12-31	11.313	1979-12-31	2.646

1978-12-31	9.688	1978-12-31	8.188	1978-12-31	2.893
1977-12-31	8.500	1977-12-31	6.958	1977-12-31	1.595
1976-12-31	10.042	1976-12-31	8.646	1976-12-31	0.497
1975-12-31	9.417	1975-12-31	7.354	1975-12-31	-1.155
1974-12-31	10.750	1974-12-31	9.313	1974-12-31	-3.861
1973-12-31	7.646	1973-12-31	6.874	1973-12-31	-1.861
1972-12-31	6.000	1972-12-31	5.358	1972-12-31	0.094
1971-12-31	6.479	1971-12-31	4.748	1971-12-31	1.571

Appendix D (Historical Exchange Rates for 1 USD)

Time	AUD	CAD	EUR	GBP	JPY	MYR	SAR	SGD	USD	AED	EGP
2000-07-01	1.67	1.48	1.05	0.66	105.76	3.80	3.750	1.72	1	3.67	3.45
2000-08-01	1.72	1.49	1.09	0.67	109.42	3.80	3.750	1.73	1	3.67	3.49
2000-09-01	1.74	1.47	1.11	0.69	106.04	3.80	3.750	1.72	1	3.67	3.51
2000-10-01	1.84	1.50	1.14	0.68	108.15	3.80	3.750	1.75	1	3.67	3.57
2000-11-01	1.91	1.53	1.16	0.69	108.41	3.80	3.750	1.74	1	3.67	3.75
2000-12-01	1.86	1.54	1.14	0.70	111.50	3.80	3.750	1.75	1	3.67	3.81
2001-01-01	1.79	1.50	1.07	0.67	114.71	3.80	3.750	1.73	1	3.67	3.84
2001-02-01	1.80	1.50	1.06	0.68	115.53	3.80	3.750	1.74	1	3.67	3.86
2001-03-01	1.90	1.54	1.08	0.69	117.32	3.80	3.750	1.75	1	3.67	3.86
2001-04-01	2.06	1.58	1.14	0.70	125.43	3.80	3.750	1.80	1	3.67	3.87
2001-05-01	1.94	1.54	1.12	0.70	122.30	3.80	3.750	1.81	1	3.67	3.90
2001-06-01	1.97	1.53	1.18	0.71	118.94	3.80	3.750	1.81	1	3.67	3.88
2001-07-01	1.97	1.52	1.18	0.71	124.47	3.80	3.750	1.82	1	3.67	3.88
2001-08-01	1.94	1.54	1.14	0.70	124.66	3.80	3.750	1.80	1	3.67	3.95
2001-09-01	1.89	1.55	1.09	0.69	118.70	3.80	3.750	1.74	1	3.67	4.27
2001-10-01	2.03	1.58	1.09	0.68	120.03	3.80	3.750	1.77	1	3.67	4.28
2001-11-01	1.96	1.59	1.11	0.68	121.83	3.80	3.750	1.83	1	3.67	4.25
2001-12-01	1.92	1.58	1.12	0.70	123.42	3.80	3.750	1.83	1	3.67	4.28
2002-01-01	1.96	1.59	1.13	0.69	131.39	3.80	3.750	1.85	1	3.67	4.58
2002-02-01	1.97	1.59	1.16	0.71	133.65	3.80	3.750	1.83	1	3.67	4.61
2002-03-01	1.93	1.60	1.16	0.70	133.31	3.80	3.750	1.83	1	3.67	4.61
2002-04-01	1.87	1.60	1.14	0.70	133.24	3.80	3.750	1.85	1	3.67	4.63
2002-05-01	1.86	1.56	1.10	0.68	127.59	3.80	3.750	1.81	1	3.67	4.62
2002-06-01	1.76	1.53	1.07	0.68	124.18	3.80	3.750	1.79	1	3.67	4.61
2002-07-01	1.78	1.52	1.01	0.65	119.94	3.80	3.750	1.77	1	3.67	4.63
2002-08-01	1.85	1.59	1.02	0.64	119.46	3.80	3.750	1.76	1	3.67	4.66
2002-09-01	1.81	1.56	1.02	0.65	118.48	3.80	3.750	1.75	1	3.67	4.61
2002-10-01	1.84	1.58	1.01	0.64	122.54	3.80	3.750	1.79	1	3.67	4.61
2002-11-01	1.79	1.56	1.00	0.64	122.06	3.80	3.750	1.76	1	3.67	4.63
2002-12-01	1.79	1.57	1.01	0.64	122.50	3.80	3.750	1.76	1	3.67	4.60
2003-01-01	1.78	1.58	0.95	0.62	118.70	3.80	3.750	1.73	1	3.67	4.62
2003-02-01	1.70	1.53	0.93	0.61	119.66	3.80	3.750	1.74	1	3.67	5.36
2003-03-01	1.65	1.49	0.93	0.64	118.07	3.80	3.750	1.74	1	3.67	5.54
2003-04-01	1.66	1.47	0.92	0.63	118.18	3.80	3.750	1.77	1	3.67	5.74
2003-05-01	1.59	1.42	0.89	0.62	118.70	3.80	3.750	1.77	1	3.67	5.90
2003-06-01	1.53	1.37	0.85	0.61	119.01	3.80	3.750	1.73	1	3.67	5.98

2003-07-01	1.48	1.35	0.86	0.60	119.56	3.80	3.750	1.76	1	3.67	6.02
2003-08-01	1.54	1.40	0.89	0.62	120.22	3.80	3.750	1.76	1	3.67	6.18
2003-09-01	1.55	1.38	0.91	0.64	116.48	3.80	3.750	1.75	1	3.67	6.15
2003-10-01	1.46	1.35	0.85	0.60	110.80	3.80	3.750	1.73	1	3.67	6.15
2003-11-01	1.42	1.32	0.86	0.59	109.52	3.80	3.750	1.74	1	3.67	6.12
2003-12-01	1.38	1.30	0.84	0.58	109.46	3.80	3.750	1.72	1	3.67	6.13
2004-01-01	1.33	1.29	0.80	0.56	107.28	3.80	3.749	1.70	1	3.67	6.16
2004-02-01	1.32	1.33	0.80	0.55	105.77	3.80	3.750	1.70	1	3.67	6.17
2004-03-01	1.29	1.34	0.80	0.54	109.03	3.80	3.750	1.70	1	3.67	6.23
2004-04-01	1.30	1.31	0.81	0.54	103.74	3.80	3.750	1.67	1	3.67	6.18
2004-05-01	1.39	1.37	0.84	0.56	110.32	3.80	3.750	1.70	1	3.67	6.24
2004-06-01	1.41	1.37	0.82	0.54	110.19	3.80	3.75	1.70	1	3.67	6.18
2004-07-01	1.42	1.33	0.82	0.55	108.21	3.80	3.75	1.72	1	3.67	6.19
2004-08-01	1.43	1.33	0.83	0.55	111.35	3.80	3.75	1.72	1	3.67	6.21
2004-09-01	1.42	1.31	0.82	0.56	109.45	3.80	3.75	1.71	1	3.67	6.21
2004-10-01	1.38	1.26	0.81	0.56	110.35	3.80	3.75	1.68	1	3.67	6.23
2004-11-01	1.34	1.22	0.78	0.55	106.38	3.80	3.75	1.67	1	3.67	6.28
2004-12-01	1.29	1.19	0.75	0.52	102.80	3.80	3.75	1.63	1	3.67	6.23
2005-01-01	1.28	1.20	0.74	0.52	102.65	3.80	3.75	1.63	1	3.67	6.15
2005-02-01	1.29	1.24	0.77	0.53	103.74	3.80	3.75	1.64	1	3.67	5.84
2005-03-01	1.27	1.24	0.76	0.52	104.34	3.80	3.75	1.62	1	3.67	5.80
2005-04-01	1.30	1.22	0.77	0.53	107.48	3.80	3.75	1.66	1	3.67	5.80
2005-05-01	1.28	1.25	0.77	0.52	104.98	3.80	3.75	1.64	1	3.67	5.80
2005-06-01	1.34	1.25	0.82	0.55	108.61	3.80	3.75	1.67	1	3.67	5.80
2005-07-01	1.33	1.24	0.83	0.56	111.46	3.80	3.75	1.69	1	3.67	5.79
2005-08-01	1.31	1.21	0.82	0.57	112.01	3.75	3.75	1.66	1	3.67	5.77
2005-09-01	1.32	1.19	0.80	0.55	110.18	3.77	3.75	1.68	1	3.67	5.77
2005-10-01	1.31	1.16	0.83	0.57	113.37	3.77	3.75	1.69	1	3.67	5.76
2005-11-01	1.34	1.18	0.83	0.57	116.63	3.78	3.75	1.69	1	3.67	5.76
2005-12-01	1.35	1.17	0.85	0.58	120.45	3.78	3.75	1.69	1	3.67	5.76
2006-01-01	1.36	1.16	0.85	0.58	117.83	3.78	3.75	1.66	1	3.67	6.04
2006-02-01	1.33	1.14	0.83	0.56	117.79	3.75	3.75	1.63	1	3.67	5.73
2006-03-01	1.34	1.14	0.84	0.57	116.05	3.71	3.75	1.62	1	3.67	5.73
2006-04-01	1.40	1.17	0.83	0.58	117.69	3.68	3.75	1.62	1	3.67	5.74
2006-05-01	1.32	1.12	0.79	0.55	113.44	3.62	3.75	1.58	1	3.67	5.74
2006-06-01	1.34	1.10	0.78	0.54	112.82	3.64	3.75	1.58	1	3.67	5.75
2006-07-01	1.35	1.11	0.78	0.54	114.51	3.67	3.75	1.59	1	3.67	5.74
2006-08-01	1.31	1.13	0.78	0.53	114.72	3.67	3.75	1.58	1	3.67	5.74
2006-09-01	1.31	1.11	0.78	0.52	117.18	3.67	3.75	1.57	1	3.67	5.74
2006-10-01	1.34	1.12	0.79	0.53	118.03	3.69	3.75	1.59	1	3.67	5.73

2006-11-01	1.29	1.13	0.78	0.52	116.99	3.65	3.75	1.56	1	3.67	5.73
2006-12-01	1.27	1.14	0.75	0.51	115.62	3.59	3.75	1.54	1	3.67	5.72
2007-01-01	1.27	1.16	0.76	0.51	118.95	3.53	3.75	1.54	1	3.67	5.71
2007-02-01	1.29	1.18	0.77	0.51	120.59	3.50	3.75	1.53	1	3.67	5.70
2007-03-01	1.27	1.17	0.76	0.51	117.54	3.51	3.75	1.53	1	3.67	5.70
2007-04-01	1.24	1.15	0.75	0.51	117.97	3.46	3.75	1.52	1	3.67	5.70
2007-05-01	1.21	1.11	0.73	0.50	119.73	3.42	3.75	1.52	1	3.67	5.68
2007-06-01	1.20	1.06	0.74	0.51	122.01	3.40	3.75	1.53	1	3.67	5.70
2007-07-01	1.18	1.06	0.74	0.50	123.26	3.45	3.75	1.53	1	3.67	5.69
2007-08-01	1.18	1.06	0.73	0.49	118.56	3.47	3.75	1.52	1	3.67	5.66
2007-09-01	1.22	1.05	0.73	0.50	116.00	3.50	3.75	1.52	1	3.67	5.66
2007-10-01	1.12	0.99	0.70	0.49	115.80	3.40	3.74	1.48	1	3.67	5.59
2007-11-01	1.09	0.95	0.69	0.48	115.04	3.34	3.74	1.45	1	3.67	5.49
2007-12-01	1.13	1.00	0.68	0.49	110.93	3.36	3.73	1.45	1	3.66	5.53
2008-01-01	1.14	0.99	0.68	0.50	111.74	3.31	3.75	1.44	1	3.67	5.53
2008-02-01	1.11	1.00	0.67	0.51	106.43	3.23	3.75	1.41	1	3.67	5.56
2008-03-01		0.98	0.66	0.50	104.08	3.19	3.75	1.39	1	3.67	5.50
2008-04-01	1.10	1.02	0.64	0.51	101.43	3.19	3.75	1.38	1	3.67	5.46
2008-05-01	1.07	1.02	0.65	0.51	104.46	3.16	3.75	1.36	1	3.67	5.36
2008-06-01		0.99	0.64	0.51	105.50	3.24	3.75	1.36	1	3.67	5.34
2008-07-01	1.05	1.02	0.63	0.50	105.79	3.27	3.75	1.36	1	3.67	5.34
2008-08-01	1.07	1.03	0.64	0.51	107.60	3.26	3.75	1.37	1	3.67	5.29
2008-09-01	1.17	1.07	0.68	0.55	108.13	3.40	3.75	1.42	1	3.67	5.37
2008-10-01	1.27	1.06	0.71	0.56	106.03	3.44	3.75	1.44	1	3.67	5.45
2008-11-01		1.22	0.78	0.62	98.33	3.55	3.75	1.48	1	3.67	5.58
2008-12-01	1.55	1.24	0.79	0.67	93.66	3.63	3.75	1.53	1	3.67	5.52
2009-01-01	1.41	1.22	0.72	0.69	90.78	3.46	3.75	1.44	1	3.67	5.52
2009-02-01		1.23	0.78	0.70	89.80	3.61	3.75	1.51	1	3.67	5.57
2009-03-01		1.27	0.79	0.70	97.65	3.71	3.75	1.55	1	3.67	5.59
2009-04-01	1.44	1.26	0.75	0.69	98.38	3.65	3.75	1.52	1	3.67	5.63
2009-05-01	1.37	1.19	0.75	0.67	99.12	3.56	3.75	1.48	1	3.67	5.64
2009-06-01	1.23	1.09	0.71	0.61	95.95	3.47	3.75	1.44	1	3.67	5.60
2009-07-01	1.24	1.15	0.71	0.61	96.62	3.52	3.75	1.44	1	3.67	5.60
2009-08-01		1.08	0.70	0.60	95.25	3.52	3.75	1.44	1	3.67	5.54
2009-09-01	1.20	1.10	0.70	0.62	93.04	3.53	3.75	1.44	1	3.67	5.52
2009-10-01	1.15	1.08	0.69	0.63	89.82	3.47	3.75	1.41	1	3.67	5.49
2009-11-01		1.08	0.68	0.61	90.48	3.41	3.75	1.40	1	3.67	5.47
2009-12-01	1.08	1.04	0.66	0.60	86.75	3.38	3.75	1.38	1	3.67	5.48
2010-01-01	1.11	1.05	0.70	0.62	92.91	3.42	3.75	1.40	1	3.67	5.49
2010-02-01	1.13	1.07	0.72	0.63	90.55	3.41	3.75	1.41	1	3.67	5.46

2010-03-01	1.11	1.05	0.74	0.67	89.19	3.39	3.75	1.41	1	3.67	5.50
2010-04-01	1.09	1.01	0.74	0.66	93.81	3.26	3.75	1.40	1	3.67	5.50
2010-05-01	1.08	1.01	0.75	0.65	94.16	3.19	3.75	1.37	1	3.67	5.56
2010-06-01	1.20	1.05	0.82	0.68	91.06	3.31	3.75	1.41	1	3.67	5.70
2010-07-01	1.19	1.06	0.80	0.66	87.72	3.24	3.75	1.40	1	3.67	5.70
2010-08-01	1.11	1.03	0.77	0.64	86.46	3.18	3.75	1.36	1	3.67	5.70
2010-09-01	1.10	1.05	0.78	0.65	84.30	3.13	3.75	1.35	1	3.67	5.71
2010-10-01	1.03	1.02	0.73	0.63	83.26	3.08	3.75	1.31	1	3.67	5.69
2010-11-01	1.01	1.02	0.72	0.62	80.53	3.09	3.75	1.29	1	3.67	5.78
2010-12-01	1.03	1.02	0.76	0.64	84.12	3.15	3.75	1.31	1	3.67	5.79
2011-01-01	0.98	1.00	0.75	0.64	81.11	3.07	3.75	1.28	1	3.67	5.80
2011-02-01	0.99	0.99	0.72	0.62	81.47	3.06	3.75	1.27	1	3.67	5.86
2011-03-01	0.98	0.97	0.72	0.61	81.94	3.03	3.75	1.27	1	3.67	5.90
2011-04-01	0.96	0.97	0.70	0.62	84.00	3.02	3.75	1.26	1	3.67	5.96
2011-05-01	0.91	0.95	0.67	0.60	81.22	2.96	3.75	1.22	1	3.67	5.95
2011-06-01	0.94	0.97	0.70	0.61	81.03	3.01	3.75	1.23	1	3.67	5.96
2011-07-01	0.93	0.96	0.69	0.62	80.77	3.01	3.75	1.23	1	3.67	5.96
2011-08-01	0.91	0.95	0.70	0.61	76.92	2.94	3.75	1.20	1	3.67	5.94
2011-09-01	0.93	0.98	0.70	0.62	76.92	2.98	3.75	1.20	1	3.67	5.96
2011-10-01	1.03	1.05	0.74	0.64	76.96	3.20	3.75	1.31	1	3.67	5.96
2011-11-01	0.97	1.02	0.73	0.63	78.28	3.12	3.75	1.28	1	3.67	5.97
2011-12-01	0.98	1.02	0.74	0.64	77.68	3.13	3.75	1.28	1	3.67	6.01
2012-01-01	0.98	1.02	0.77	0.64	77.18	3.17	3.75	1.30	1	3.67	6.03
2012-02-01	0.93	1.00	0.76	0.63	76.15	3.04	3.75	1.25	1	3.67	6.03
2012-03-01	0.93	0.99	0.75	0.63	81.22	3.01	3.75	1.25	1	3.67	6.04
2012-04-01	0.96	1.00	0.75	0.63	82.96	3.06	3.75	1.26	1	3.67	6.04
2012-05-01	0.97	0.98	0.76	0.62	80.15	3.03	3.75	1.24	1	3.67	6.03
2012-06-01	1.03	1.04	0.81	0.65	78.13	3.20	3.75	1.29	1	3.67	6.04
2012-07-01	0.98	1.02	0.79	0.64	79.69	3.17	3.75	1.27	1	3.67	6.05
2012-08-01	0.95	1.00	0.82	0.64	78.31	3.11	3.75	1.25	1	3.67	6.07
2012-09-01	0.97	0.99	0.80	0.63	78.37	3.12	3.75	1.25	1	3.67	6.10
2012-10-01	0.97	0.98	0.78	0.62	78.00	3.06	3.75	1.23	1	3.67	6.10
2012-11-01	0.96	1.00	0.77	0.62	80.09	3.05	3.75	1.22	1	3.67	6.11
2012-12-01	0.96	0.99	0.77	0.62	82.39	3.04	3.75	1.22	1	3.67	6.11
2013-01-01	0.96	0.99	0.76	0.62	86.58	3.06	3.75	1.22	1	3.67	6.34
2013-02-01	0.96	1.00	0.73	0.64	92.24	3.11	3.75	1.24	1	3.67	6.72
2013-03-01	0.98	1.03	0.77	0.67	93.16	3.09	3.75	1.24	1	3.67	6.74
2013-04-01	0.96	1.02	0.78	0.66	93.54	3.09	3.75	1.24	1	3.67	6.80
2013-05-01	0.97	1.01	0.76	0.64	97.42	3.04	3.75	1.23	1	3.67	6.94
2013-06-01	1.05	1.04	0.77	0.66	100.58	3.10	3.75	1.26	1	3.67	6.98

2013-07-01	1.08	1.05	0.77	0.66	99.54	3.17	3.75	1.27	1	3.67	7.03
2013-08-01	1.12	1.03	0.76	0.66	99.03	3.24	3.75	1.27	1	3.67	6.99
2013-09-01	1.12	1.05	0.76	0.64	98.28	3.29	3.75	1.28	1	3.67	6.99
2013-10-01	1.07	1.03	0.74	0.62	98.09	3.24	3.75	1.25	1	3.67	6.89
2013-11-01	1.06	1.04	0.74	0.63	98.57	3.17	3.75	1.24	1	3.67	6.89
2013-12-01	1.10	1.06	0.74	0.61	102.47	3.23	3.75	1.25	1	3.67	6.88
2014-01-01	1.12	1.06	0.73	0.60	105.29	3.28	3.75	1.26	1	3.67	6.95
2014-02-01	1.14	1.11	0.74	0.61	102.13	3.35	3.75	1.28	1	3.67	6.96
2014-03-01	1.12	1.11	0.72	0.60	101.82	3.28	3.75	1.27	1	3.67	6.96
2014-04-01	1.08	1.10	0.72	0.60	103.53	3.26	3.75	1.26	1	3.67	6.97
2014-05-01	1.08	1.10	0.72	0.59	102.34	3.26	3.75	1.25	1	3.67	7.01
2014-06-01	1.07	1.08	0.73	0.60	101.79	3.21	3.75	1.25	1	3.67	7.15
2014-07-01	1.05	1.06	0.73	0.58	101.50	3.21	3.75	1.25	1	3.67	7.15
2014-08-01	1.07	1.09	0.74	0.59	102.65	3.21	3.75	1.25	1	3.67	7.15
2014-09-01	1.07	1.09	0.76	0.60	104.28	3.16	3.75	1.25	1	3.67	7.15
2014-10-01	1.14	1.12	0.79	0.62	109.16	3.27	3.75	1.27	1	3.67	7.15
2014-11-01	1.14	1.13	0.80	0.63	112.05	3.29	3.75	1.29	1	3.67	7.15
2014-12-01	1.18	1.13	0.80	0.64	118.38	3.42	3.75	1.31	1	3.67	7.15
2015-01-01	1.23	1.16	0.83	0.64	120.27	3.52	3.75	1.33	1	3.67	7.16
2015-02-01	1.29	1.27	0.88	0.66	117.24	3.63	3.76	1.35	1	3.67	7.58
2015-03-01	1.28	1.25	0.89	0.65	119.68	3.61	3.75	1.36	1	3.67	7.63
2015-04-01	1.32	1.26	0.93	0.67	119.74	3.69	3.75	1.37	1	3.67	7.62
2015-05-01	1.27	1.21	0.89	0.66	119.95	3.58	3.75	1.33	1	3.67	7.62
2015-06-01	1.31	1.25	0.92	0.66	124.67	3.68	3.75	1.35	1	3.67	7.63
2015-07-01	1.31	1.26	0.91	0.64	123.04	3.76	3.75	1.35	1	3.67	7.63
2015-08-01	1.37	1.31	0.91	0.64	123.92	3.83	3.75	1.37	1	3.67	7.83
2015-09-01	1.42	1.32	0.88	0.65	119.86	4.19	3.75	1.41	1	3.67	7.83
2015-10-01	1.42	1.33	0.89	0.66	119.86	4.42	3.75	1.43	1	3.67	7.83
2015-11-01	1.40	1.31	0.91	0.65	120.56	4.28	3.75	1.40	1	3.67	8.03

Appendix E (Project Activity and Milestone Details)

Task Name
Project Milestone
Contract Milestone
Contract Sign Date
Ready for Commercial Operation
Physical Hand Over of Site
Interim Milestones
GT 12 - Receipt at Site
GSU Transformer 12 - Receipt at site
GT 11- First Fire
GT12- First Fire
GT - PO Award
GT 11- Erection Start
GT12- Turning Gear
GT 11- Synchronization
GT 12- Synchronization
GT 11- Performance Test
GT 12- Performance Test
Start of Piling
GT 11 - Receipt at Site
GSU Transformer 11 - Receipt at site
GT 11- Turning Gear
GT 12- Erection Start
GT 11- Reliability Test Start
GT 12- Reliability Test Start
MEW Interfaces
Waste Water -Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
Earthing - Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
Service Water -Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
Potable Water - Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
Fire Water - Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
Gas Oil - Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
Fuel Gas - Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
400 KV Substation - Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
Telemetry to NCC - Tie In Approval from MEW and Existing Plant O&M Agency (ZSPS)
I&C Signals for Interconnected Facilities - Tie In coordinate Finalization & MEW Approval
Intercom, Loud Speaker & Time Distribution System - Tie In coordinate Finalization
Engineering
Basic Engineering
Prepare & Submit- DCDs

Prepare & Submit- Plot Plan
Prepare & Submit- GA Drawings
Preparation of Equipment Lists
Prepare & Submit- Piping Dwgs & Lists
Prepare & Submit- Civil Foundation & Load Details
Approve DCDs
Approve Plot Plan
Approve GA Drawings
Approve Equipment Lists
Approve Piping Dwgs & Lists
Approve Civil Foundation & Load Details
Detailed Engineering
Civil, Structural & Arch Drawings
Prepare & Submit- Pile Layout and Design document - GTG Area
Approval Pile Layout and Design document - GTG Area
Foundations Dwgs
GT& GTG Building - Review & Approve- Foundation Design & Dwgs
GSU & Other Transformers - Review & Approve Foundation Design & Dwgs
Pipe Rack - Review & Approve - Foundation Design and dwgs
GTG Auxiliary - Review & Approve - Foundation Design & Dwgs
Gas Conditioning Building - Review & Approve - Foundation Design & Dwgs
By Pass Stack - Review & Approve - Foundation Design & Dwgs
Gas Compressor - Review & Approve - Foundation Design & Dwgs
Gas Conditioning Area Equipment - Review & Approve - Foundation Design & Dwgs
Diesel Generator - Review & Approve - Foundation Design & Dwgs
General Aux Equipment - Review & Approve - Foundation Design & Dwgs
General Aux Building - Prepare & Submit Foundation Design & Dwgs
General Aux Building - Review & Approve - Foundation Design & Dwgs
OCM Building & Equipment - Review & Approve - Foundation Design & Dwgs
Store Buildings & Open Storage - Review & Approve - Foundation Design & Dwgs
Dyke Wall dwgs & Gas Oil Tank - Prepare & Submit Foundation Design & Dwgs
GT& GTG Building - Prepare & Submit- Foundation Design & Dwgs
Gas Oil Tank Foundation and Dyke Wall dwgs - Review & Approve
DM and Service water Tanks - Prepare & Submit Foundation Design & Dwgs
Approve . Foundation - DM and Service Water Tanks
GTG Area - Prepare & Submit - Foundation Design & Dwgs
OCM Building & Equipment - Prepare & Submit Foundation Design & Dwgs
General Aux Building Equipment - Prepare & Submit - Foundation Design & Dwgs
GSU & Other Transformers - Prepare & Submit Foundation Design & Dwgs
Store Buildings & Open Storage - Prepare & Submit Foundation Design & Dwgs
Pipe Rack - Prepare & Submit Foundation Design & Dwgs
Gas Conditioning Building - Prepare & Submit Foundation Design & Dwgs
Diesel Generator - Prepare & Submit Foundation Design & Dwgs
Gas Compressor - Prepare & Submit Foundation Design & Dwgs

Gas Conditioning Area Equipment - Prepare & Submit Foundation Design & Dwgs
By Pass Stack - Prepare & Submit Foundation Design & Dwgs
GTG Auxiliary - Prepare & Submit Foundation Design & Dwgs

Structural Dwgs

GT Building - Review & Approval Steel Structure Dwg
Ducts & Trenches - Prepare & Submit Dwgs Civil Drg
Storm/Drainage Water System - Review & Approval of Dwg
Prepare & Submit- Arch/Concrete design and dwgs Car Park
Car Park Dwg - Review & Approval
Storm/Drainage Water System - Prepare & Submit Dwg
Ducts & Trenches - Review & Approval Civil Dwg
GT Building - Prepare & Submit Steel Structure Dwg
OCM Building - Prepare & Submit Structural Dwg
General Aux Building - Prepare & Submit Structural Dwg
Store Building - Prepare & Submit Structural Dwg
Gas Conditioning Building - Prepare & Submit Structural Dwg
Gas Oil Forwarding Pump House - Prepare & Submit Structural Dwg
SW/DM/PW Pump Shed - Prepare & Submit Structural Dwg
Other BOP Building - Prepare & Submit Structural Dwg
GT Building - Review & Approval Civil Structure Dwg
OCM Building - Review & Approval Structural Dwg
General Aux Building - Review & Approval Structural Dwg
Store Building - Review & Approval Structural Dwg
Gas Conditioning Building - Review & Approval Structural Dwg
Gas Oil Forwarding Pump House - Review & Approval Structural Dwg
SW/DM/PW Pump Shed- Review & Approval Structural Dwg
Miscl. BOP structures - Review & Approval Structural Dwg
GT Building - Prepare & Submit Civil Structure Dwg
Preparation of HVAC Package
Fire Water under Ground Services - Prepare & Submit Dwg
Fire Water under Ground Services - Review & Approval of Dwg
Preparation of Fire Alarm and Fire Fighting Package

Architectural Dwgs

GT Building - Prepare & Submit Arch Dwg
OCM Building - Prepare & Submit Arch Dwg
General Aux Building - Prepare & Submit Arch Dwg
Store Building - Prepare & Submit Arch Dwg
Gas Conditioning Building - Prepare & Submit Arch Dwg
Gas Oil Forwarding Pump House - Prepare & Submit Arch Dwg
SW/DM/PW Pump Shed - Prepare & Submit Arch Dwg
GT Building - Review & Approval Arch Dwg
OCM Building - Review & Approval Arch Dwg
General Aux Building - Review & Approval Arch Dwg
Store Building - Review & Approval Arch Dwg
Gas Conditioning Building - Review & Approval Arch Dwg
Gas Oil Forwarding Pump House - Review & Approval Arch Dwg

SW/DM/PW Pump Shed - Review & Approval Arch Dwg

Mechanical - System

Calculations

Review and Approve Calculation- Water Supply & Treatment Systems
Review and Approve Calculation- Demineralized Water (DM) System
Review and Approve Calculation- Compressed Air System
Prepare Calculation- Fire Fighting & Fire Alarm System
Prepare and Submit Calculation- Water Supply & Treatment Systems
Prepare and Submit Calculation- Service Water System
Prepare Calculation- Plant Drainage System / Waste Water System
Prepare Calculation- HVAC (Air Flow Diagram)
Prepare Calculation- Closed Circuit Cooling System
Prepare and Submit Calculation- Compressed Air System
Prepare Calculation- Gas Oil System
Prepare Calculation- GT Wash Water System
Prepare and Submit Calculation- Demineralized Water (DM) System
Prepare Calculation- Fuel Gas system

PIDs & System Descriptions

Preparation of PID- GTG
Review & Approve PID - GTG
Prepare and Submit of PID- Emergency Disel Generator
Review & Approve PID - Emergency Disel Generator
Prepare & Submit PID- Fire Fighting System
Prepare and Submit of PID- Water Supply & Treatment Systems
Prepare & Submit PID- Plant Drainage System
Prepare & Submit PID- HVAC (Air Flow Diagram)
Prepare & Submit PID- Closed Circuit Cooling System
Prepare & Submit PID- Compressed Air System
Preparation of PID- Gas Oil System
Prepare & Submit PID- GT Wash Water System
Prepare and Submit PID- Demineralized Water (DM) System
Prepare & Submit PID- Fuel Gas system
Preparation of PID- Fin Fan Cooler Interconnect Piping
Review & Approve PID Fire Fighting & Fire Alarm System
Review & Approve PID - Water Supply & Treatment Systems
Review & Approve PID - Plant Drainage System
Review & Approve PID HVAC (Air Flow Diagram)
Review & Approve PID Closed Circuit Cooling System
Review & Approve PID Compressed Air System
Review PID Gas Oil System
Review PID GT Wash Water System
Review and Approve PID- Demineralized Water (DM) System
Review & Approve PID Fuel Gas system
Review & Approve PID Fin Fan Cooler Interconnect Piping

Specifications

Preapare Isometrics all systems

Prepare Specification - GTG
Prepare Specification- Fuel Gas Conditioning System
Prepare Specification- Compressed Air System
Prepare Specification Fuel Gas Compressors
Prepare Specification- Field & Shop Fabricated tanks
Prepare Specification- Chiller & HVAC System
Prepare Specification- Misc Pumps
Prepare Specification- Fin Fan Cooler & Heat Exchangers
Prepare Specification- Emergency DG System
Prepare Specification- DM Plant
Prepare Specification- Cranes, Hoists& Lifting Devices
Prepare Specification- Gas Oil System
Prepare Specification- Fire Fighting & Fire Alarm System
Prepare Specification- GTG Exhaust System
Prepare Specification- Motor Operated Valve
Prepare Specification- Pipes & Valves
Electrical System
Electrical Calculation
Prepare & Submit Calc- Lightning Protection System Calculation
Review Calc Power System Studies for Overall Plant (Short Circuit, Analysis)
Review & Approve Calc Power System Studies for Overall Plant (Load Flow, Motor Starting)
Review & Approve Calc Overall Protection Setting Study and Report
Review & Approve Calc CT & VT Sizing Calculation
Review & Approve Calc GSU Sizing Calculation
Review & Approve Calc GCB Sizing Calculation
Review & Approve Calc UT Sizing Calculation
Review & Approve Calc UAT /SAT Sizing Calculation
Review & Approve Calc MV Switchgear Sizing Calculation
Review & Approve Calc LV Switchgear Sizing Calculation
Review & Approve Calc EDG Sizing Calculation
Review & Approve Calc Bus Duct-Iso Phase Sizing Calculation
Review & Approve Calc Bus Duct-LV System Sizing Calculation
Review & Approve Calc DC & UPS Sizing Calculations
Review & Approve Calc MV Cable Sizing Calculation
Review & Approve Calc LV Cable Sizing Calculation
Review & Approve Calc Earthing System Calculation
Review & Approve Calc Lightning Protection System Calculation
Prepare Calc- Power System Studies for Overall Plant (Short Circuit, Analysis)
Prepare Calc- Power System Studies for Overall Plant (Load Flow, Motor Starting)
Prepare & Submit Calc- Overall Protection Setting Study and Report
Prepare & Submit Calc- CT & VT Sizing Calculation
Prepare & Submit Calc- GSU Sizing Calculation
Prepare & Submit Calc- GCB Sizing Calculation
Prepare & Submit Calc- UT Sizing Calculation
Prepare & Submit Calc- UAT /SAT Sizing Calculation

Prepare & Submit Calc- MV Switchgear Sizing Calculation
Prepare & Submit Calc- LV Switchgear Sizing Calculation
Prepare & Submit Calc- EDG Sizing Calculation
Prepare & Submit Calc- Bus Duct-Iso Phase Sizing Calculation
Prepare & Submit Calc- Bus Duct-LV System Sizing Calculation
Prepare & Submit Calc- DC & UPS Sizing Calculations
Prepare & Submit Calc- MV Cable Sizing Calculation
Prepare & Submit Calc- LV Cable Sizing Calculation
Prepare & Submit Calc- Earthing System Calculation
Electrical Drawings
Prepare Cable Pulling and termination sheets
Prepare & Submit- Raceway Layouts
Approve Raceway Layouts
Prepare & Submit- Earthing Layouts
Approve Earthing Layouts
Prepare & Submit- Cable Schedule for GTG system
Prepare & Submit- Cable Schedule for BOP system
Review & Approve Cable Schedule for GTG system
Review & Approve Cable Schedule for BOP system
Prepare & Submit- InterConnection Schedule for GTG system
Prepare & Submit- InterConnection Schedule for BOP system
Approve InterConnection Schedule for GTG system
Approve InterConnection Schedule for BOP system
Prepare & Submit- Key SLD
Review & Approve Key SLD
Equipment/Material Procurement Specifications-Data sheet
Prepare Spec- GSU Transformer
Prepare Spec- Unit Transformer
Prepare Spec- Generator Circuit Breaker
Prepare Spec- MV Transformer
Prepare & Submit Spec- LV Switchgear & MCC
Prepare Spec- DC & UPS System (Including Fuse Board)
Prepare Spec- MV/ LV Switchgears
Prepar Spec- Isolated Phase Bus Duct
Prepare Spec- 400 KV HV Power Cables & Accessories
Prepare Spec- MV/LV Power Cables
Prepare Spec- Control & Instrumentation Cables
Prepare Spec- Emergency Diesel Generator (EDG)
I&C
I&C Drawings and Documents
Prepare - DCS Graphics Drawing
Prepare & Submit- Control System Configuration Drawing (overall DCS Architectural Diagram)
Prepare & Submit- Plant Control Philosophy
Prepare- I&C Power Supply Distribution Philosophy
Prepare - Control Logic Drawing

Prepare - Control Loop Drawing
Prepare- I&C Signal Interfacing With Existing Facilities
Review - DCS Graphics Drawing
Review & Approve - Control System Configuration Drawing (overall DCS Architectural Diagram)
Review & Approve - Plant Control Philosophy
Review - I&C Power Supply Distribution Philosophy
Review - Control Logic Drawing
Review - Control Loop Drawing
Review & Approve - I&C Signal Interfacing With Existing Facilities
Prepare & Submit - Schematic /Wiring /Circuit Drawings
Review & Approve - Schematic /Wiring /Circuit Drawings
Prepare Cable Pulling and termination sheets
I&C Specification and Data Sheets
Prepare Spec- Distributed Control System (DCS)
Prepare Spec- CCTV
Prepare Spec- Field Instruments
Prepare Spec- Continuous Emission Monitoring System (CEMS)
Prepare Spec- Pneumatic Control and On-Off Valve
Procurement
Construction / Erection
Commissioning