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A Total Cost Approach to Supply Chain Risk Modeling

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ABSTRACT

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The modern supply chain is long, complex, interconnected and global, and plays a fundamental role in business competitiveness. These conditions, along with various supply chain management trends in recent years have increased risks in supply chains which threaten supply chain performance. Greater impact, especially on cost, from an increased threat of supply disruptions is one area of particular concern. Companies today are struggling to find effective means to manage this increased risk and avoid adverse financial impacts.

An approach to managing supply disruption risk in supply chains based on the minimization of the total cost of ownership (TCO) of the supply chain is explored in this thesis. Insights are provided into an appropriate view of supply chain risk and a general four step risk management process to guide the design and evaluation of a new risk management tool based on such an approach. A prototype of the new total cost-based, modeling and simulation tool was created in partnership with ProModel Corporation and a government contractor that requested to remain anonymous. A preliminary assessment of the effectiveness of this tool in minimizing TCO and providing an interface useable by non-modelers is provided. This study also reviews and compares a sample set of current supply chain risk management methods and tools and compares them with the new tool for relevance in aiding users in managing supply disruption risk.

Based on literature findings and preliminary feedback from pilot contextual demonstrations of the tool, the total cost approach to risk modeling appears promising, although the execution needs to be improved with further enhancements made to the prototype tool. In this preliminary study and evaluation, sufficient evidence is not available to determine that the new prototype tool is any more effective than other currently available risk management tools to provide necessary information to make supply chain risk management decisions that minimize TCO of a supply chain. Suggestions for further development of the tool, especially for improvement of the total cost approach, are provided as well as a preliminary evaluation procedure and survey instruments for a more robust evaluation of the new tool.

Keywords: Brian Jeffery Saunders, disruption risk, risk management, risk mitigation, risk modeling, supply chain management, SCM, supply chain risk, supply chain risk management, SCRM, supplier disruption risk, supply disruption risk, total cost, Total Cost of Ownership, TCO

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TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

The modern business environment is one marked by an increasingly complex network of global suppliers and customers. “[Today] every company … either sources globally, sells globally, or competes with some company that does” (Mentzer, Stank, and Myers 2007). In this increasingly interconnected economic environment success is becoming less today about company competing against company and much more about supply chain competing against supply chain. The increased competitiveness, complexity, and length of supply chains (Tummala and Schoenherr 2011), as well as industry trends in supply chain management practices over the last several years, such as lean manufacturing techniques ("Identify and Reduce Supplier Risk" 2010), have also increased risk in supply chains. Companies today are becoming not only more dependent on, but are also more threatened by the increased global competition and increased vulnerability to risk in such lengthy, complex, and interconnected supply chains (Faisal, Banwet, and Shankar 2006; Rice 2011). This competitive and risk laden business environment faced by today’s companies is increasing the need for effective tools and methods for designing, assembling, and coordinating high-performance supply chains.

The combination of increased supply chain length, complexity, and current industry trends has created greater exposure and vulnerability to adverse impacts on performance due to increased risk in supply chains. Of particular concern is the increased risk of supply chain failures (Tummala and Schoenherr 2011), specifically in the form of supply disruption where a supplier’s ability to either produce or transport goods is impeded for some reason. In today’s highly competitive and risk laden environment it is becoming more important for companies to have an improved ability to effectively identify, assess, and mitigate the risk associated with supply disruption in order to remain viable and competitive since "even minor business disruptions can have [devastating ripple effects] in a supply chain" that is long and complex (Norrman and Jansson 2004), and the negative economic consequences can be severe and long lasting.

While awareness of this increased exposure to supply disruption risks and associated consequences seems to be increasing (McBeath 2011a), companies still don't have good methods or tools to deal with these risks ("Identify and Reduce Supplier Risk" 2010; Wilson 2010) resulting in adverse financial impacts. "Unanticipated and unnecessary costs [are] widely recognized, [but] … to a large degree, [they are] accepted as part of business" and "most risk assessment and mitigation tools [stop] at raising alerts to potential problems…[and] lack the ability to provide clear guidance on what to do when disruption does occur" (Peters 2010). Supply chain managers need better tools to provide a clearer understanding and strategy for managing the risk associated with disruptions in today's supply chains, ultimately leading to the ability to make better sourcing and planning decisions.

This thesis explores whether a tool can be developed that more effectively provides information needed to manage supply disruption risk and thereby minimize the total cost of ownership of a supply chain. Specifically, this thesis provides input for the design and a preliminary evaluation of the effectiveness of a proof-of-concept modeling and simulation-based analysis tool using a total cost approach as compared to alternative supply chain risk management tools currently available.

1.1 Background

1.1.1 Supply Chains and Supply Chain Management

Supply chains are nothing new. Since the time of maritime trade in the Byzantine Empire, the movement of goods along the Silk Road across Asia, and almost certainly in times predating either of those, businesses and individuals have relied on a network of various entities to produce and deliver goods demanded by end customers. Yet while supply chains themselves have existed for ages, the understanding and management of supply chains as a crucial part of business is a relatively new discipline. The idea and recognition of the importance of supply chain management (SCM) has been around at least since the 1950's, but it wasn't until the 1980's that the term supply chain management began to appear (Mentzer et al. 2001) and it was in the 1990's that the discipline really began to come into its own.

In the first decade of the 21st century supply chain management has seen an increased focus on supply chain risk, giving rise to supply chain risk management (SCRM) and a new area of focus and study for the discipline. New tools, methods, and approaches for supply chain risk management have been developed and previous approaches modified to reflect this increased focus on risk. In 2008, for example, an updated version of the Supply Chain Council's popular Supply Chain Operations Reference (SCOR) model was released with a specific Supply Chain Risk Management module (http://supply-chain.org/membership), and in 2009 the International Organization for Standardization (ISO) published a new standard for risk management called ISO 31000:2009. Despite the progress made in recent years, the area of risk management in the supply chain management discipline is still quite young (Faisal, Banwet, and Shankar 2006; Zsidisin et al. 2004) and in need of further research and development for more wide-spread and effective application.

1.1.2 Supply Chain Risk

Increasingly complex, lengthy, and global supply chains are exposed to both a greater number and a broader range of risks, including supply disruption risks, which occur more frequently and have potentially more severe financial and other impacts on supply chain performance. Several conditions seem to be contributing to the increased risk of supply disruptions. Among these conditions, today's global supply chains are exposed to more economic and political uncertainty as the number of sourcing markets increases (Myers, Borghesi, and Russo 2007). Additionally, the size of modern supply chain networks create increased sourcing lead times, a greater number of "middlemen," a reduction in control for sourcing firms, and an increase in exposure to natural disasters because of geographic dispersion (Ibid.). Due to their greater dependence on technology for coordination and operation, there is also an increased exposure to technological failures in modern supply chains (Ibid.). The complexity and interconnections in supply chains have also decreased visibility for individual organizations in the chain, which is another reason for such increased risk ("Identify and Reduce Supplier Risk" 2010) and increased potential for greater negative consequences from such risks (Manuj, Dittman, and Gaudenzi 2007). In addition, industry trends in supply chain management and design in recent years have further increased exposure to supply chain risks for many companies lacking the appropriate capabilities and network design to handle disruptions or changes in supply chain operation. The trend in recent years has been toward lean supply chains (Liker 2004) with just-in-time inventory management systems as a means of increasing value delivery to customers in an increasingly customer centric and competitive business environment.

Though the effects of lean and other trends are largely positive (McBeath 2004), they have increased exposure to risks due to reduced responsiveness and resiliency when disruptions occur and increased pressures to reduce costs (Manuj, Dittman, and Gaudenzi 2007) and time-to-market (Norrman and Jansson 2004). “Responsiveness often demands buffers with respect to capacity, lead time and inventory, which also help increase resilience to supply chain disruptions” (Melnyk et al. 2010), yet such buffers are often reduced or eliminated as companies seek to implement Lean principles and remain competitive under current industry trends. Companies need new tools and methods that allow them to maintain the performance improvements brought by Lean and other techniques but increase supply chain resilience through effective management of supply disruption risks.

There is an additional set of conditions and specific supply chain challenges being faced by the defense industry, the industry ultimately at the focus of this study, and the United States Department of Defense (DoD) that further increase the need to cost-effectively deal with supply disruption risks. Declining defense budgets in recent years have resulted in consolidation of the defense industry supply base (Arnseth 2010), and as a result there has been a reduction in domestic production capacity. With this consolidated supply base, it can be difficult to find suppliers with the proper capabilities in quality and production capacity. This also makes it especially difficult to find multiple sourcing options which is also problematic since “consolidating supply chain functions…exposes firms to increased risks from a less than diversified portfolio of partners” (Myers, Borghesi, and Russo 2007). This increase in supply chain risk due to supplier consolidation is also manifesting itself in the private sector (Cavinato 2004; Murphy 2009), but defense firms are particularly subject to this increased risk when, for political or security reasons, government contracts require that suppliers be based in the US. Furthermore, customer demand in the form of government contracts can be volatile because of economic and political considerations, leading to additional disruption risk exposure as the supply base struggles to remain viable under uncertain demand conditions.

Examples of supply chain disruptions in recent years demonstrate the risks that companies face today. Such disruptions have led to an increased awareness of their negative effects on supply chain performance and the need for effective decision support tools in designing resilient supply chains and quickly meeting the need to reconfigure or reconstitute a disrupted supply chain in a cost-effective manner. One prominent example is the Phillips factory fire in 2000. Two large cell phone manufacturers, Ericsson and Nokia, faced supply shortages in March 2000 when lightening started a fire in a Philips Semiconductor plant in Albuquerque, New Mexico and destroyed inventories and shut down the plant for six weeks (Tomlin 2006). While Nokia was able to shift production to other suppliers, Ericsson suffered major losses upwards of $400 million, largely because, like many companies still today, it lacked appropriate tools and methods to identify and mitigate the risk and appropriately respond and manage the risk when the disruption occurred. The March 2011 earthquake and tsunami in Japan provides another recent example of the need for effective supply chain risk management tools. While the full effects of the disaster are still unknown, the effects continue to be felt months later in the electronic and automotive industries where Japanese suppliers play a key role in the supply chain. Japanese automakers, such as Toyota, stand to lose thousands of sales because of necessary production cutbacks at plants, even in North America, and expected to run plants at far below pre-disaster production levels at least through mid-summer 2011 (Welsh 2011). The recent worldwide economic downturn and resulting “credit crunch” has also increased awareness and focus on supply disruptions due to financial and economic risks.

1.2 Problem Statement

Companies today appear to recognize the increasing risk of supply chain disruption, but efforts to proactively and effectively manage such risk seems to be lacking. This is due, at least in part, to the unavailability of effective methods for formulation of mitigation strategies. Current prevalent methods of supply chain design and management often ignore the realities of risks and are ineffective at minimizing the cost and exposure to the negative impacts of supply disruption risks.

1.2.1 Supply Chain Risk Management Tools and Methods

The need for a more effective approach to managing supply chain risk seems apparent, yet the appropriate approach remains in question. In recognition of the need to better identify, mitigate, and manage risk in their supply chains, the government and large defense contracting firms (Wilson 2010) are investing in the development of new supply chain risk management tools to aid in risk management of their supply chains. In multiple recent issues of *Inside Supply Management*, the Institute of Supply Management, a well-known and well respected organization in the supply management discipline, has published multiple articles about managing disruption risk in supply chains, providing further evidence that this is a current and important issue for companies and the field of supply chain management. The interest and activity in this area of supply chain management indicates that current models, methods, and practices are either insufficient or ineffective in meeting the needs of many companies, leaving many ill-equipped to manage risk and leading many others to simply avoid the problem. Recent surveys (McBeath 2011a; Schneider 2008) found that many companies recognize the importance and intend to improve their supply chain risk management methods and technologies, but also found many simply aren't doing it, likely because they don't know how and good tools aren't available to help them.

Multiple tools and methods are available and others are in development to aid in supply chain risk management. These include benchmarking and mapping approaches, cause-and-effect diagrams, and various discrete-event and Bayesian network based simulation and modeling tools. It is difficult, however, to know where each tool may be useful and effective and where there may be gaps in risk management needs not addressed by current tools. Some methods focus primarily on identification of risks, others focus on predicting the likelihood of identified risks, and others still include an approach that is not concerned with the source or likelihood of risk but only the management of risk events. Some tools may be effective in identifying and predicting risks but they may not provide input on effective means of managing those risks.

1.2.2 Supply Chain Total Cost of Ownership

One important goal and challenge in supply chain management is the minimization of supply chain costs through the optimization of supply chain configuration, coordination, and procurement decisions. The traditional method of supplier selection and supply chain design, especially in the realm of government contracting, tends to be based on the lowest bid price. This is referred to as a "three bids and a buy" approach where bids are taken from three potential suppliers and the lowest bid is taken and is sometimes mandated by law. Such a strategy may be effective in an ideal, risk-free world, but in the real world where supply chain risks are present this strategy can rarely be expected to achieve the lowest total cost of ownership (TCO) for an individual product or the complete supply chain.

Melnyk et al. (2010) argue that while cost minimization is the ultimate objective of supply chain management, it is not enough in the current business environment to just source from the “low cost” providers, wherever they are in the world, and focus only on traditional improvement efforts centered around business processes for improving quality and delivery speed. Rather, they argue, supply chains should be managed and designed to consider factors beyond the traditional cost-related benefit alone, such as responsiveness, security, sustainability, resilience, and innovation. Given the realities of supply disruption risk and following the logic of these authors, supply chains must be designed for security and resilience in order to minimize the occurrence of disruption and to “[ensure] that the supply chain can recover quickly and cost-effectively [when] disruptions” do occur.

Minimizing the traditional purchase cost considerations alone, and ignoring consequences and costs associated with supply disruption risk, will leave a supply chain unresponsive to customer needs and will increase exposure to the negative effects of potential supply disruptions including increased total costs. Companies that do not have effective contingency and mitigation plans for minimizing total supply chain costs in the event of supply disruption will stand to lose more during a disaster or other event leading to failure than their better prepared counterparts, as seen in the case of Ericsson and the Philips factory fire.

1.3 Thesis Objectives

The primary objective of this thesis is to see if a new tool and method can be developed that is more effective than current tools and methods at providing the information necessary to make supply chain risk management decisions that minimize total cost of ownership of a supply chain. Specifically, this thesis provides a design (functional) specification for this tool and a preliminary evaluation of its effectiveness in minimizing the cost impact of supply disruptions in a supply chain. This thesis also provides recommendations for further enhancements of the tool and method.

1.3.1 Total Cost Tool for Risk Modeling

The new method and solution prototype tool developed will be referred to in this thesis as the Risk Supply Chain Model, or RSC*Model*. It was developed by a non-profit organization (referred to in this thesis as the Lead Non-Profit Organization) focused on developing manufacturing supply chain solutions in conjunction with ProModel Corp. and the author of this thesis under a government funded contract. The author's contribution was to review literature and industry practice pertaining to related work in this area, provide input on the functional specification, develop a preliminary evaluation instrument for assessing its effectiveness, and provide an overall assessment. The concept and premise for development of RSC*Model* was based on the idea that an effective supply chain analytical tool mitigates the effects of supply chain risk related to supplier loss by minimizing the cost impact of supply disruption in a supply chain through tactics that enable and optimize the design, assembly, and coordination of manufacturing supply chains, including the ability to quickly reconfigure or reconstitute a disrupted supply chain (Peters 2010). As such, the RSC*Model* tool is intended to be a predictive analytic tool that a Supply Chain manager or Program Manager (PM) can use to assess the impact of supply disruption on supply chain performance and to determine the best way to manage those risks to minimize the impact on performance, including cost. The RSC*Model* tool is built on a reusable discrete-event simulation framework, and is intended to be useable by individuals with no modeling experience. The preliminary tool evaluation for this thesis is based on the initial proof-of-concept development of RSC*Model*.

1.4 Hypothesis

The working hypothesis of this thesis is that RSC*Model* is no more effective than current tools and methods in providing the information necessary to make supply chain risk management decisions that minimize total cost of ownership of the supply chain.

1.5 Methodology

The methodology followed for this thesis included the following steps, performed in cooperation with other participating individuals and organizations:

1. Determine customer needs
2. Assess current technologies and practices
3. Develop a functional specification
4. Develop a prototype discrete-event simulation based tool
5. Do a pilot contextual demonstration
6. Survey users in the pilot contextual demonstration
7. Assess the effectiveness of the tool along three key dimensions:
    - Minimization of Supply Chain Total Cost of Ownership
    - Ease of Learning & Use
    - Comparative Advantages & Disadvantages in Functionality

The approach taken to address these objectives and ultimately the hypothesis of this thesis is in several parts. Preliminary research for the initial concept of RSC*Model* was completed by the Lead Non-Profit Organization on the project. Further refinement of the concept and development of a functional specification was guided by development and administration of surveys to a target government "buyer" organization partnering on the project and several of their suppliers aimed at gaining a better understanding of customer needs. Ongoing input from team members, including the author, also helped guide the development of a functional specification and subsequent development of the proof-of-concept and prototype simulation tool. This input and feedback included suggestions for improving the tool's user interface and output reports for greater ease of use as well as suggestions for functional modifications.

This thesis includes a review of literature to provide a basis for viewing and understanding risk in supply chains and to identify and assess current supply chain risk management methods and tools and identify current gaps in functionality. The RSC*Model* tool could then be qualitatively compared to currently available tools and methods to identify potential shortcomings and advantages of RSC*Model* as well as additional criteria or considerations that should be included in the tool, ultimately to identify areas where potential improvements in supply chain risk management may exist through the use of RSC*Model*. An evaluation of three other government funded supply chain analysis tools recently or currently in development also plays an important role in this methodology and assessment of effectiveness. Each tool was evaluated and a preliminary assessment made for potential opportunities of future integration between each to enhance supply chain risk management and to leverage investments across multiple development projects.

Another method employed for assessment of the effectiveness of RSC*Model* is through the gathering and reporting of feedback from practicing supply chain professionals who participated in pilot demonstrations of the tool. Due to restrictive government policies and practices in effect on this Department of Defense-funded project, the empirical information that was able to be obtained for this preliminary assessment is limited. While it was hoped at the outset of this thesis that a pilot implementation could be carried out with a set of practicing supply chain experts being presented with a highly structured, hands-on scenario to provide a robust approach for evaluation of RSC*Model* with subsequent feedback generation for the key dimensions of “effectiveness” outlined, the limitations, access restrictions, and time consuming procedures and policies required of the project hampered these efforts. The preliminary design concept for such a robust evaluation procedure was developed before ultimately focusing efforts on a more concise evaluation instrument. A brief survey instrument was prepared and reviewed by other project members and leaders as a guide for gathering of feedback from supply chain practitioners following live contextual demonstrations of the prototype RSC*Model* tool using a real-world implementation scenario with data from the partnering government “buyer” organization. The feedback gathered is used to make preliminary assessments of ease of use and learning and the ability to minimize the impact on performance, including cost, of supply disruption risks, and to identify any additional suggestions for improvement.

1.6 Contribution

As explained, the modern business world is in need of better ways to manage supply chain risk. There are a myriad of supply chain management tools and methods available and it is difficult to know which are effective and in what ways. This thesis provides input on effective supply chain risk management tool design based on review of literature, including a review of a sample set of current tools and methods, as well as a preliminary empirical assessment of the prototype RSC*Model* tool and a conceptual comparison to other current tools reviewed.

1.7 Assumptions and Delimitations

While there are multiple supply chain risks worthy of study and of great concern to modern supply chains, this research is limited to only one aspect of supply chain risk, namely the risk of supply disruption (either temporary or permanent) with a primary emphasis on supplier disruption risk. Additionally, this study is also focused on the effectiveness of supply chain management tools for minimizing the cost impact of a risk event and not on the identification, reduction, or elimination of root causes of risks or the probability that those risks will occur.

The analysis of alternative tools to the RSC*Model* tool is necessarily limited for this study to supply chain risk management tools perceived to have some relevance for managing supply disruption risk and those that are either commercially available or discussed in the literature. The exception to this is the examination of tools in development under United States government contracts for which contacts have been made available through the RSC*Model* development team. The examination of these alternative tools is also limited to a review and assessment of the various capabilities, functionality, and uses of each tool as explained in available literature and as explained by contacts involved in current tool development.

Although the RSC*Model* tool is being developed with the ability to evaluate both supply chain disruption risk and supply chain agility scenarios at the same time, this thesis will be limited to assessing the tool on the basis of the disruption risk functionality alone. Also, the RSC*Model* tool is a pilot project and is designed to look at only a single part for analysis in a relatively simple supply chain thus limiting its current application, although, selection of the part to analyze is recognized as an important step in the risk management process as some parts are likely to pose a greater risk to supply chain performance if disrupted than others. In the future, RSC*Model* could look at an "entire system" with more complexity, helping to identify high risk parts. Additionally, the intent to both provide input and assess effectiveness of the RSC*Model* tool during development has made this study challenging. As such, some suggestions offered for improvement of the tool are not incorporated as part of the initial phase of tool development and assessment.

Finally, this thesis is looking only at the total cost of ownership for a supply chain as it relates to the supply disruption risk. It is beyond the scope of this thesis, and the RSC*Model* tool in its preliminary stage of development, to assess all supply chain related costs. Also, RSC*Model* and this thesis are not concerned with the implications for cost, or other impacts, from risk transfer techniques or activities (for example, traditional insurance plans). Finally, RSC*Model* is also not concerned with determining the optimal supply chain service level and its associated costs. The total cost analysis is therefore limited to the assessment of total cost specific to the risk of supply disruption with the goal of maintaining a 100% service level.

1.8 Definition of Terms

- **Configuration (of supply chain):** The decision of where to geographically locate the value-added activities of the supply chain.
- **Coordination (of supply chain):** The decision of how the different geographically dispersed activities of a supply chain are going to be linked or integrated.
- **Consequence (of risk):** "the significance of ... loss to the organization" resulting from a risk event (Zsidisin et al. 2004).
- **Contingency Plans:** A contingency plan is a plan devised to guide the response following the occurrence of a risk event that was impractical or otherwise impossible to avoid in order to minimize the impact.

- **Impact (of risk):** The effect or influence (extended consequence) that a risk event has on supply chain performance (cost, service level, etc.).
- **Magnitude (of risk):** The degree and duration, or (immediate) severity of a risk event (e.g. the magnitude of an earthquake, number of striking workers and for how long, etc.)
- **Probability (of risk):** “A measure of how often a detrimental event that results in a loss occurs” (Zsidisin et al. 2004); the potential or likelihood of occurrence of a risk event within some time frame.
- **Reconfiguration (of a supply chain):** The act of rearranging the elements of the supply chain.
- **Reconstitution (of a supply chain):** The restoration of the elements and/or processes of a disrupted supply chain for recovery of supply chain performance, potentially through reconfiguration.
- **Recovery (of a supply chain):** Returning the supply chain to its previous or original state of performance prior to disruption.
- **Resilience (of a supply chain):** “[E]nsures that the supply chain can recover quickly and cost-effectively from disruptions …” (Melnyk et al. 2010).
- **Risk:** “Exposure to the possibility of loss, injury, or other adverse or unwelcome circumstance” (*Risk, N.* 2010), or more simply, exposure to danger or peril.
- **Risk Assessment (or, Risk Analysis):** The activity in which identified risks are analyzed to develop an understanding of the risk, including: determining the likelihood of occurrence and the range of possible consequences in either quantitative or qualitative terms and evaluating the “priority for attention” that should be given to address the risk (Campbell 2004; Purdy 2010).

- **Risk Event:** The actual occurrence of the possible event associated with a risk and the corresponding exposure to and realization of the resulting loss or undesirable outcome.
- **Risk Identification:** Determining and understanding what uncertain future events could happen as well as how, when, and why they could happen (Campbell 2004; Purdy 2010).
- **Risk Management:** "The identification, assessment, and prioritization of risks followed by coordinated and economical application of resources to minimize, monitor, and control the probability and/or impact of unfortunate events" (Hubbard 2009).
- **Risk Mitigation:** The effort to reduce the probability of exposure and/or severity of the consequences (e.g. degree, duration, and/or impact on performance) of a risk. In this thesis risk mitigation is used generally to encompass the concepts of contingency plans, risk mitigants, and controls. (Controls typically affect probability and "mitigants" and contingency plans are focused on affecting consequences, with contingency plans typically doing so after a risk event has occurred.) Risk mitigation plays a role in the overall risk management process as the means by which risk treatment occurs.
- **Risk Monitoring:** The activity that assesses the effectiveness of risk treatment, determines when overall risk is reduced because of the implementation of risk management plans or because risk events have occurred, and ensures appropriate action occurs as new risks emerge and existing risks change (Campbell 2004; Purdy 2010).
- **Risk Transfer:** The shift of risk consequences from one party to another, such as through insurance.
- **Risk Treatment (Risk Handling):** The process/activity in which existing controls, risk mitigation strategies, or contingency plans are either modified or new ones developed and

implemented to minimize the impact of risk (Campbell 2004; Faisal, Banwet, and Shankar 2006; Purdy 2010).

- **Risk Trigger:** A condition that increases the likelihood of a risk event occurring.
- **Supplier Disruption Risk:** A specific supply disruption risk that one or more suppliers in a supply chain suddenly lose some or all of their capacity to deliver requested goods (or services) for a determinate or indeterminate time period.
- **Supply Chain:** "A set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer" (Mentzer et al. 2001).
- **Supply Chain Management (SCM):** "The systemic, strategic coordination of the traditional business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole" (Mentzer et al. 2001)**.**
- **Supply Chain Risk:** The probability that an event of some magnitude will occur that results in a loss or undesirable impact on supply chain performance.
- **Supply Chain Risk Management (SCRM):** The branch of the Supply Chain Management discipline that deals specifically with the challenges supply chain risks pose to long-term performance of individual companies and the supply chain as a whole.
- **Supply Disruption Risk:** A specific supply chain risk that an event occurs that results in the disruption to the desired flow of goods (or services) in the supply chain. A supply disruption can occur either at the supplier location (*supplier* disruption) or in the process of transporting or delivering those goods to the next supplier or customer downstream (*transportation* disruption).

- **Total Cost of Ownership (TCO):** "Total cost of ownership (TCO) is a purchasing tool and philosophy which is aimed at understanding the true cost of buying a particular good or service from a particular supplier" (Ellram 1995). From a supply chain perspective, it is a holistic measurement of all supply chain related activity and procurement costs, including both direct and indirect costs, incurred through execution of a supply strategy for sourcing all required goods or services. (May also be called Total Ownership Cost, TOC).

2 LITERATURE REVIEW

The risk management capability of the Risk Supply Chain Model (RSC*Model*) tool is the focus of this thesis. A review of current and past research efforts and industry practice for risk management dealing with supply disruption risk in supply chains is presented and summarized in this chapter. The review of literature provides a basis for identifying current views, understanding, attitudes, approaches, and practices in the supply chain risk management discipline specific to supply chain disruption risk and where potential areas for improvement exist. Additionally, a set of current supply chain risk management methods and tools are identified and reviewed such that they can be assessed and gaps in functionality identified.

2.1 Risk

An understanding of “risk” provides an important foundation for the development and assessment of any risk management tool. Fischhoff, Watson, and Hope (1984) explain that "risk is a focal topic in management of many activities … [and] for that management to be successful, an explicit and accepted definition of the term 'risk' is essential." However, a review of the literature reveals that “there are many different definitions of risk” (Purdy 2010) and "the meaning of 'risk' has always been fraught with confusion and controversy" (Fischhoff, Watson, and Hope 1984) and is often used without consideration of different uses, adding to the confusion.

The Oxford English Dictionary online defines risk as “exposure to the possibility of loss, injury, or other adverse or unwelcome circumstance” (Risk, N. 2010), or expressed even more simply, risk is exposure to peril or danger. This represents the layman’s view of risk and the general way in which the term is used in everyday speech. As this general view implies, risk is composed of two aspects or components: probability (a measure of “exposure to the possibility”) and consequence (the peril or danger) (Campbell 2004; Chapman 1997; Holton 2004; Manuj, Dittman, and Gaudenzi 2007; Sharp et al. 2009). This basic relationship can be expressed as an equation as shown below.

$$\text{Risk} = \text{Probability} \times \text{Consequence} \tag{2-1}$$

This general definition provides the basis for understanding the basic components of risk which, in a broad view such as this, is a simple concept. However, once one explores the technicalities and application of the term “risk” in a specific area or discipline, this simple view of risk falls short and the confusion quickly grows as the exact meaning of the term is often not clear. As noted later, a more precise definition of risk plays an important role in determining the level of risk since one cannot evaluate and prioritize risk if it is not properly defined what is being measured.

When looking in a general sense at supply chain or other business related risk, some authors introduce the concept of risk being the possibility of an event that has negative consequences (Chapman 1997; Manuj, Dittman, and Gaudenzi 2007; Sharp et al. 2009). Sharp defines risk as “the possibility of suffering a harmful event,” and Chapman explains risk to be “a combination of the probability of a negative event and its consequences.” Similarly, Manuj, Dittman, and Gaudenzi define risk as “an expectation that an adverse event will occur that will be detrimental to the stakeholders in the supply chain.” This can be expressed with a slight modification to Equation 2-1 as shown by Sharp:

$$Risk \; = Probability \text{ of an event} \times Consequence \text{ if the event happens} \tag{2-2}$$

Or, in a slightly more complex manner Manuj, Dittman, and Gaudenzi show consequences as the sum of losses associated with an adverse event:

$$\mathrm{R}_{\mathrm{Risk\ Event\ n}} \; = \mathrm{P}_{\mathrm{Event\ n}} \times (\mathrm{L}_1 + \mathrm{L}_2 + \mathrm{L}_3 + \cdots + \mathrm{L}_\mathrm{m})_{\mathrm{Event\ n}} \tag{2-3}$$

Where R is the risk of event n, P is the probability of event n happening, and L represents the losses from event n. This presents the idea that there may be multiple consequences from any single risk event that should be considered as part of the risk.

Other definitions of risk take a slightly different focus. Another attempt at a general definition of risk is "exposure to a proposition of which one is uncertain" (Holton 2004). This also implies a probability or chance of exposure to a consequence, but through a different concept. This definition of risk focuses on the concept of uncertainty, with uncertainty implying the possibility of exposure to a result different than that expected or desired. Taking the focus on uncertainty to another level, the concept of risk begins to include a focus on objectives. In discussing uncertainty and risk, Zsidisin et al. (2004) imply uncertainty to mean that an organization currently does not possess all required information to achieve its objectives for the future. As part of an effort to eliminate confusion and to support a new, simple, and unified way of thinking about, approaching, and defining risk and risk management, the International Organization for Standardization (ISO) published a new standard for risk management in 2009 called ISO 31000:2009. The hundreds of experts from 28 countries participating in the standard development agreed to define risk as the “effect of uncertainty on objectives” (Purdy 2010). This definition also focuses on risk as variation in “consequences,” or outcomes, related to objectives but additionally emphasizes that risk is not only about what could happen (the possibility of an event) and what the immediate consequences are of that event, but also what effect it could have on other current and future objectives.

The focus on the effect of risk on objectives in the ISO definition is important and agrees with concepts of other authors. From the point of view of the ISO definition, "… risk is the consequence of an organization setting and pursuing objectives against an uncertain environment … [and] … uncertainty arises from those internal and external factors and influences that it does not completely control but that may cause an organization to fail to achieve its objectives or may cause [a] delay" in meeting those objectives (Purdy 2010). Manuj, Dittman, and Gaudenzi (2007) also state that “in the corporate world, risk represents threats to the value the stakeholders or owners have in the business,” which relates to risk’s effect on objectives since a main objective of the business is to create and deliver value for the stakeholders. Risk then is the result of trying to achieve a goal for which one does not have complete control of all relevant factors or variables. The concepts of uncertainty and objectives is also used in the literature to imply that risk entails not only the possibility of loss but also of a gain, particularly when used to refer to financial and program or project management risk (Campbell 2004; Purdy 2010). Since the purpose and focus of this thesis is on disruption risk, this positive aspect of risk will not enter into play.

A key concept about understanding specific types of risk is related to the concept of objectives. In exploring the process and difficulties in creating an agreed upon definition of risk for technologies, Fischhoff, Watson, and Hope (1984) put forth that for a specific use of the term, there is no one universal definition. These authors explain that any definition of risk used for analysis must be bound, and the first step in defining the risk is specifying which “dimensions,” or consequences, it should include. The process of selecting and specifying those consequences depends largely on what the objectives are which differs for each organization (Kleindorfer and Saad 2005).

As in the ISO standard, attempts have been made to develop a universal definition of risk, but they still remain helpful only in a general sense as they leave too much room for interpretation to be practically applied in a specific area. In reviewing the ISO standard, Purdy recognizes this limitation and notes that practical guidance on use of the definition and standard is lacking. The main concept from all these authors appears to be that while risk can be understood on a high level with basic definitions, to be useful for guiding risk management efforts in a particular case, risk needs to be defined more specifically by identifying the objectives and the variables, or factors, which affect those objectives. Additionally, the consequences that will be used to measure risk for prioritizing management efforts need to be clearly defined.

Despite the many differences in the specifics in meaning in use of the term risk, authors either state or imply at least two general principles that are applicable for any use of the term. First, to be a risk there must be uncertainty about the future (Campbell 2004; Holton 2004; Purdy 2010). This is implied in the general definition that there must be the “possibility” of the consequence occurring. Risk is about what “could happen and what it could lead to” (Purdy 2010). If there is no uncertainty (i.e. the consequence is certain to happen), then you simply have a “problem” not a “risk” (Campbell 2004). Campbell further specifies that a past loss is not a risk because it has already occurred (Campbell 2004). Second, a risk must have a consequence for the subject in question, which for this study is limited to negative consequences. This is also implied in the general definition in that one must be "exposed" to a loss or adverse circumstance. Whether the subject recognizes or considers those consequences is not important, but only if the subject would care about the consequence if the risk occurred (Holton 2004). That means the risk must have some effect on the subject, and in particular, an effect on the ability of the subject to meet its objectives (Manuj, Dittman, and Gaudenzi 2007; Purdy 2010) which serve as a filter to determine "exposure" or concern with the risk. If there is no difference in what would be expected to happen anyway, or the consequence is inconsequential, then there is no risk (Campbell 2004; Chapman 1997).

2.1.1 Supply Chain Risk

RSC*Model* is focused on supply chain risk, and more specifically supply disruption risk and the threat it poses to supply chain performance. As discussed earlier, general definitions of risk are helpful in understanding the basic concept of risk, but as Fischhoff, Watson, and Hope (1984) explain, a more specific definition of risk is needed for specific application of the term since the definition of risk can change with circumstance. For proper analysis of RSC*Model*, therefore, a further exploration is needed of risk and risk management as it ultimately pertains to supply disruption risk and its impact on supply chain performance.

Like all risk, supply chain risk is still composed of probability and consequences where probability is "a measure of how often a detrimental event that results in a loss occurs" and consequence is "the significance of ... loss to the organization" (Zsidisin et al. 2004). Mentzer et al. (2001) define a supply chain as "a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer." Based on this definition of a supply chain and the previous definitions and discussion of risk, a more useful definition of risk for supply chains would include the probability of an event occurring that results in negative effects (consequences) on the flows of products, services, finances, and/or information from a source to a customer including the cost associated with creating and maintaining those flows.

Also as indicated, risk comes from uncertainty in meeting objectives. Based on the definition and purpose of a supply chain, the primary objective in the supply chain is to maximize performance in terms of creating and maintaining the flow of goods, services, etc. A classic trade-off in supply chain management is between the service level created by the "flow" of goods, services, finances, and/or information, and the cost to create the necessary flow to achieve the service level. The service level represents one aspect of the "performance" of the supply chain, often in terms of how often the supply chain can get the right thing, to the right customer, at the right time, in the right quantity and quality. Cost is another closely related basic measure of supply chain "performance," and the service level maintained can ultimately be related to cost. Typically the higher the service level delivered by the supply chain the higher the cost will be, but also the higher the potential financial benefit, although techniques and best practices can be implemented to alter the trade-off (maintain service level with lower cost, maintain cost while increasing service level, etc.). Ultimately, a drop in service level can be related to a cost in terms of lost current and future revenues, goodwill, etc. This cost-service trade-off adds complexity to supply chain management decisions since finding and executing at the optimal level of cost and service is difficult and differs depending on objectives, strategy, and circumstances. Effective supply chains often pursue a combination of outcomes or strategies in an effort to be more adaptable to new business environments and more responsive to the needs of critical customers (Melnyk et al. 2010), with each having a different impact for cost and service.

Whatever set of objectives and conditions exist that affect the trade-off, the ultimate objective comes back to achieving the supply chain flow that optimizes supply chain performance to allow the organization to best serve its target customers at the lowest cost. A general definition for supply chain risk would then be the probability that an event will occur that results in a loss or undesirable impact on supply chain performance.

There are many reasons why there is risk in supply chains that threatens performance. There are many uncertainties related to the ability of the supply chain to achieve the needs and objectives of the organization and its stakeholders, and there seems to be more now than ever. Faisal, Banwet, and Shankar (2006) note that the source of supply chain risk is the uncertainty surrounding environmental, organizational or supply chain related variables that affect the "supply chain-outcome variable," or in other words, the supply chain performance objectives. From Chapter 1, we see that multiple authors note various current supply chain conditions and practices that are increasing the number and severity of risks in supply chains. Trends such as Lean manufacturing can limit available safety nets and global outsourcing is creating long, complex, interdependent supply networks with reduced visibility and different and more numerous risks at each link throughout the chain (Faisal, Banwet, and Shankar 2006; Manuj, Dittman, and Gaudenzi 2007). As noted, these conditions create a situation where even small problems can become big problems.

Pioneering authors Womack and Jones (1996) argue that "Lean Thinking" is the antidote to waste or muda that plagues much of industry and unnecessarily increases costs, slows delivery, and results in poor quality. Womack and Jones argue that lean techniques, inspired by Toyota Motor Corporation's Toyota Production System (TPS), are key methods for obtaining world class reductions in cost, lead time, inventory, quality, and other production measures that ultimately result in greater value delivery to customers. For more than a decade “lean production” has dominated manufacturing trends (Liker 2004) and indeed this has led to vast improvements in productivity and service levels (McBeath 2004). However, as companies have applied these principles to their supply chains they have also reduced inventories throughout the supply chain to low levels with little safety stock ("Identify and Reduce Supplier Risk" 2010), ultimately reducing supply chain resilience by leaving little margin for error. “Unfortunately, the very characteristics that make supply chains cost-effective also make them vulnerable to the volatile global environment in which they exist” (Myers, Borghesi, and Russo 2007). “The leaner and more integrated supply chains get, the more likely uncertainties, dynamics and accidents in one link affect the other links in the chain” (Norrman and Jansson 2004).

Beyond lean techniques, globalization, supplier consolidation and rationalization, and other trends already discussed, Faisal, Banwet, and Shankar (2006) indicate that "lack of trust [is] one of the major factors that contributes to supply chain risks." Another important condition already introduced is that of low supply chain visibility ("Identify and Reduce Supplier Risk" 2010). The more global, competitive, and customer centric environment has also created a trend where companies must have shorter product life-cycles, compressed time-to-market, faster and heavier ramp-up of demand early in product life cycles in order to remain competitive, and extreme pressures to continually reduce costs (Chagares 2011; Manuj, Dittman, and Gaudenzi 2007), all of which result in more exposure to supply chain risks (Norrman and Jansson 2004) since it becomes harder to achieve the demanded level of performance and any disruption can create a major setback. Indeed, a recent report ("Best Practices for Supply Chain Improvement" 2011) finds that uncertainty in supply chains results in at least four key supply chain conditions decreasing performance: added cost, increased inventory levels, increased lead-times, and reduced speed to market. All of these areas run counter to achieving the objectives businesses have for their supply chains. Indeed, 60-80% of responding companies to the survey also indicated a high to medium impact on costs and time due to uncertainty in the supply chain.

The negative economic consequences of supply chain disruptions can be and often are severe and long lasting. Kleindorfer et al. show in a study of the U.S. chemical industry that disruptions from disasters, accidents, and other risk events "have led to huge economic losses and environmental damages" (Kleindorfer et al. 2003; Kleindorfer and Saad 2005). Studies by Hendricks and Singhal (2003; 2005a; 2005b) find that publicly traded firms suffering supply chain disruptions typically experience significant reductions in operating income, measures of return (ROA, ROI, etc.), stock price and shareholder value, face slower sales growth and higher growth in costs, and typically do not recover from these economic impacts for two years or more.

2.1.2 Areas of Supply Chain Risks

As described, there are many different areas of risk in supply chains mentioned in the literature that threaten their performance and achievement of objectives. This thesis does not seek to identify or provide an exhaustive discussion of all possible risks in a supply chain that could contribute to total supply chain risk; however, it is instructive to consider the various major risk areas that might exist to create a context for the focus of the RSC*Model* tool on supply disruption risk.

Several authors explain some different views and breakdowns of supply chain risks. Kleindorfer and Saad (2005) identify two broad categories of supply chain risk; (1) problems with coordinating supply and demand, and (2) disruptions to normal activities. This distinction fits well with the objectives of RSC*Model* as both a "risk" and an "agility" modeling and analysis tool with supply-demand coordination issues being primarily a supply chain agility problem while disruptions to normal activities relates to the disruption risk analysis functionality of RSC*Model*. Manuj, Dittman, and Gaudenzi (2007) make a different distinction describing that some losses from supply chain risk events affect the supply side of the supply chain while others affect the demand side. They go on to define four broad categories of risks in supply chains: supply risk, operational risk, demand risk, and security risk. In a recent 2010 publication, IndustryWeek and D&B Supply Management Solutions identify five top supply chain risk "factors": country of origin, shipment and delivery accuracy, physical security, internal processes, and social and environmental responsibilities ("Identify and Reduce Supplier Risk" 2010).

These distinctions imply that there are not only many different areas of risk but also many levels and many different specific supply chain risks in each area. For example, within each broad category of risk identified by Manuj, Dittman, and Gaudenzi, there are multiple "subrisk" categories identified. Their category of "supply risk" is defined as "the possibility of an event associated with inbound supply that may cause failures from the supplier(s) or the supply market[,] such that the outcome results in the inability of the focal firm to meet customer demand within anticipated costs or causes a threat to customer life and safety." Subrisk areas for this category include supplier reliability (capability, quality, or capacity issues), moral hazard (suppliers aren't incentivized to do what's best for the focal firm or whole supply chain), involuntary disruption of supply, price escalation, technology access, and quality issues. "Operational risk" is defined as the "possibility of an event affecting the focal firm's internal ability to produce goods and services, the quality and timeliness of production, and the profitability of the company" and includes risk areas such as limited production flexibility, technology obsolescence, inadequate manufacturing or processing capability, etc. "Demand risk" is defined as “the possibility of an event associated with the outbound supply that may affect the likelihood of customers placing orders with the focal firm or with the variance in the volume and assortment desired by the customer” and includes risks due to delayed product introductions, overstock and understock, variation in demand, etc. “Security risk” is the threat of a third party stealing data or knowledge, tampering with information or goods, or otherwise destroying, upsetting, or disabling a firm’s operation and "may manifest itself in many forms, including an adverse event affecting information, intellectual property, physical goods, and human resource security.”

For the five top supply chain risk factors identified by Industry Week and Dunn & Bradstreet, the first factor, “country of origin,” is concerned with the physical location of suppliers (supply chain configuration) and the various risks to supply chain performance due to security and other location dependent threats. Second, “shipment and delivery accuracy,” is concerned with the ability of suppliers to consistently deliver supplies on time which implies many possible risk events. For example, the mode of transportation can affect the level of risk for inaccurate shipments and delayed deliveries as can the choice of shipping lanes used due to increased likelihood of natural disasters or other factors. Their third risk area is “physical security” which is concerned with the threat to the physical safety of goods being supplied by the supplier due to inadequate facility security measures to protect goods from all types of intrusions. Fourth, “internal processes” is concerned with risks relating to controls put in place during the manufacturing process, such as inadequate quality controls, etc. Fifth, “social and environmental responsibilities,” is concerned with child labor laws, fair treatment of employees, safe working conditions, proper processing and removal of harmful chemicals (e.g. lead in paint on Chinese-made toys), etc. This risk area also includes many possible risk events such as a threat that breaking legislation will result in a shutdown of suppliers or other cause for a holdup of goods in the supply chain.

Faisal, Banwet, and Shankar (2006) note other broad categorizations of risk that exist such as political, economic, terrorism related and "other," and categorizations of risk by other authors based on their impact on business and its environment. Schneider (2008) categorized supply chain risks as "traditional" and "non-traditional," with traditional including supplier failure and continuity of supply risk categories and non-traditional including brand, reputation, regulatory compliance, product safety, and catastrophe exposure risk areas. Other authors mention or imply many similar risk areas as those already identified and many possible specific risk events. These could include risks from the possibility of events such as specific natural disasters, employee strikes , medical epidemics (Kleindorfer and Saad 2005; Melnyk et al. 2010), currency/foreign exchange rate fluctuations ("Identify and Reduce Supplier Risk" 2010; Murphy 2009; Zsidisin et al. 2004), financial/economic downturns and supplier instability (Galluzzi 2009c; "Identify and Reduce Supplier Risk" 2010; Murphy 2009), product quality and material issues including over specification in product design, raw materials depletion (Lynch 2010), and many others. One other risk mentioned is "knowledge risk," which is the concept of a negative event that is going to occur but of which the affected organization(s) has(have) no knowledge ("Risk Management" 2011). The implication here is that the "uncertainty" requirement of risk can be satisfied simply based on one's point of view.

These definitions of risk areas and identified "subrisks" demonstrate the vast number of ways that supply chain performance can be negatively affected. Indeed, even at a "subrisk" level there are multiple risk events that could lead to the subrisk. From these descriptions of various risks we can see that nearly any risk in the supply chain could occur as a result of a number of other risks. When examined more closely, these various categorizations of risks indicate that it is often a series of various risks, each leading to subsequent risks that ultimately result in an event directly causing a negative consequence of relevance to the focal firm and the performance of the supply chain. This demonstrates a point of confusion not explored in depth by most authors when discussing different supply chain risks: the connections that exist between various supply chain risks. A teleconference and presentation provided to the RSC*Model* team about the development of another government funded supply chain risk management tool (Sharp and Anderson 2011) and related explanations by Fenton and Neil (2006a; 2006b) show how risk in supply chains really needs to be viewed in a hierarchical or "causal chain" fashion.

The important concept here in thinking about supply chain risks is that the consequences of many risks in the supply chain may include the realization of another risk. Fenton and Neil present the concept of causal chains or "risk maps" that links risks together in a cause and effect type manner and describe three basic "elements" of risk that describe the causal relationships: triggers, risk events, and consequences. A risk event, as implied by the basic definition of risk, is the actual event that could or does occur that results in some negative effect occurring. Consequences, then, are described as the negative impact of a risk event. The concept of a "risk trigger" is presented by several authors and practicing supply chain managers (Fenton and Neil 2006a; Fenton and Neil 2006b; Kleindorfer and Saad 2005; Manuj, Dittman, and Gaudenzi 2007; Sharp and Anderson 2011) as something that leads to or increases the possibility of a risk event. Other events, actions, or conditions can be the "trigger" that leads to the occurrence of a risk event. Some authors simply present this concept in terms of conditions that tend to increase the probability and/or impact of certain supply chain risks. An example of a risk trigger, event, and consequence offered by Manuj, Dittman, and Gaudenzi is that of new port inspection regulation that results in, or triggers, the delay of goods achieving port clearance and therefore creating a disruption in supply.

Two additional concepts related to the causal chain view of risk presented by Fenton and Neil are that of controls and mitigants. Controls are described as something that intervenes to alter (hopefully lowering) the probability of a risk event occurring. The purpose of a control is to prevent a risk from occurring in the first place, and therefore avoiding the associated negative consequences. A mitigant is described as something that helps avoid or reduce the consequences of a risk event. Controls and mitigants are typically actions or conditions put in place by someone trying to “mitigate” a risk to reduce its impact. A simple example and diagram, adapted from Fenton and Neil (2006b), showing how risk trigger, event, consequence, control and mitigant elements are related in a causal chain is shown in Figure 2.1.

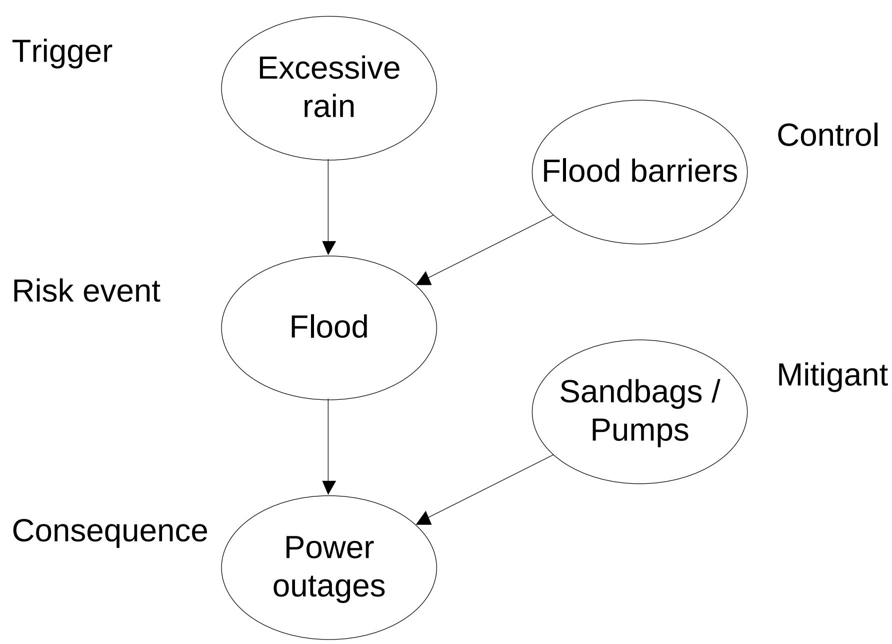

Figure 2.1 – Simple causal chain or risk map example

Fenton and Neil go on to describe that not only are all of the different elements of a causal chain for risk related they are ultimately all the same and the terminology is purely a matter of perspective. In Figure 2.2 the simple example of a risk causal chain is expanded to show additional elements.

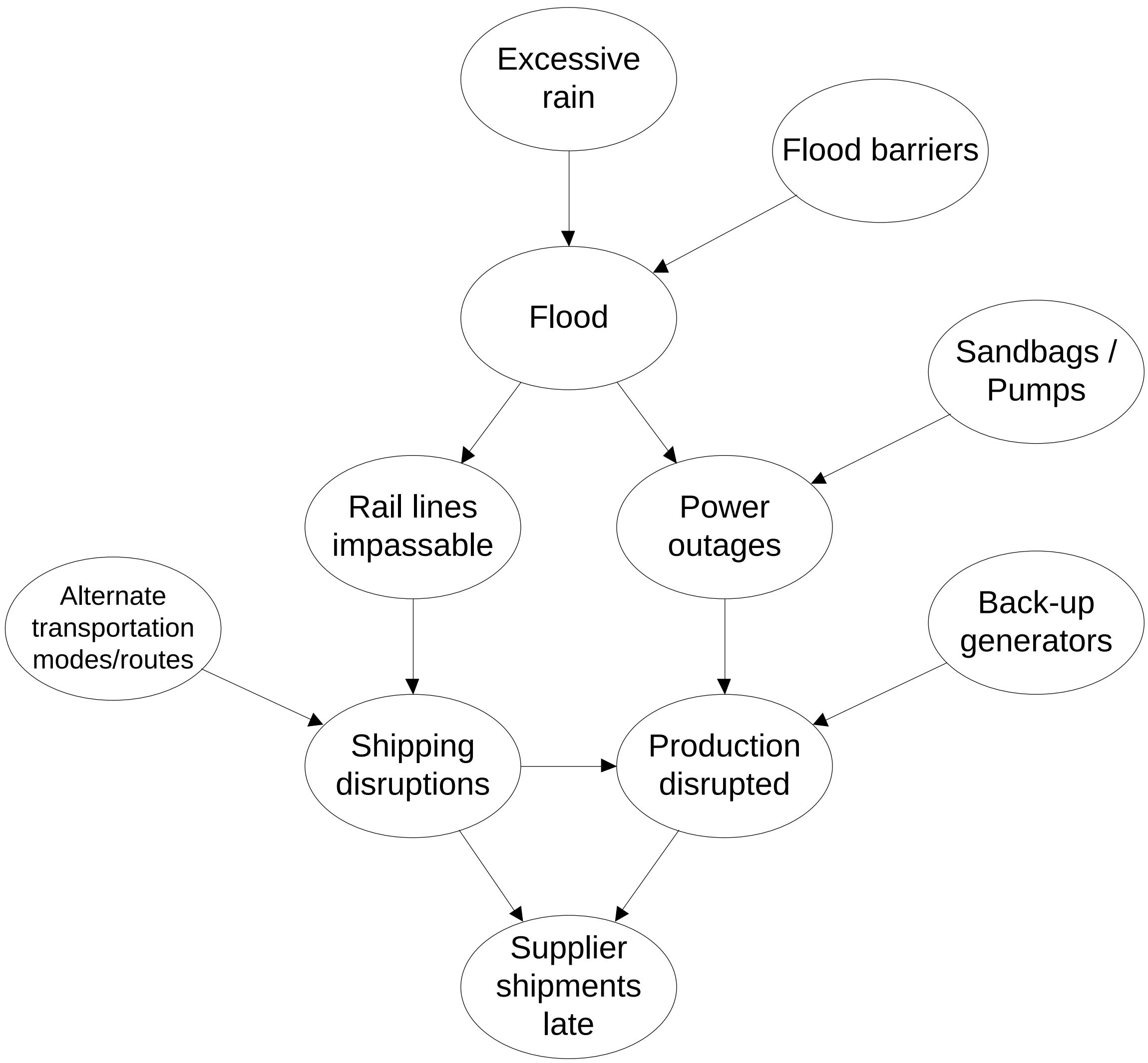

Figure 2.2 – Expanded example of risks in simple causal chain

In this expanded example, it is no longer clear which element is which. For example, "flood" can now be considered the trigger for "power outages," and "power outages" is now the event that leads to the consequence of disrupted production. Other controls and mitigants are also added. In the case of the use of sandbags and pumps, this can now be viewed as both a control and a mitigant. Fenton and Neil further explain that even controls and mitigants could in some cases be viewed as events and triggers. In this simple example, it is the highest level trigger of "excessive rain" that is the ultimate root cause of supplier shipments being late. It is easy to see how this causal chain could be expanded even further.

As discussed later, for the RANGER project this causal chain concept has been used with a research based method to identify a broad set of possible supply chain risk "elements" and to map those risk elements into a network of causal chains which ultimately link to a set of ten supply chain "performance drivers" (the performance drivers representing supply chain performance objectives or outcome variables and corresponding metrics such as on time delivery, etc.) (Sharp and Anderson 2011). While many authors, such as those mentioned above, group identified risks into categories or some type of classification, it appears very few attempt to map the various connections that might exist between risks and between risks and performance outcomes.

2.1.3 Disruption Risk

Now that supply chain risk has been reviewed at a high level, it is now possible to explore the more specific area of supply disruption risk that the RSC*Model* tool intends to address. That stated focus of the RSC*Model* tool is on "supplier" disruption risk. Supplier disruption risk occurs when one or more suppliers in a supply chain suddenly lose some or all of their capacity to deliver requested goods (or services) for a determinate or indeterminate time period. Despite the distinction and stated focus of the RSC*Model* tool more specifically on "supplier" disruption risk there appears to be no reason why it could not address more generally “supply” disruption risk, where the disruptions modeled and analyzed could be from any event that results in a disruption to the desired *flow* of goods (or services) in the supply chain (including late deliveries, and inaccurate quantities or quality of goods) and could occur either at the supplier location or in the process of transporting or delivering those goods to the next supplier or customer downstream as shown in Figure 2.3. The focus of this thesis is, therefore, focused more generally on “supply” disruption risk. Supply disruption risk could be defined more specifically as a specific supply chain risk that an event occurs that results in the disruption to the desired flow of goods (or services) in the supply chain that occurs either at the supplier location or in the process of transporting or delivering those goods to the next supplier or customer downstream.

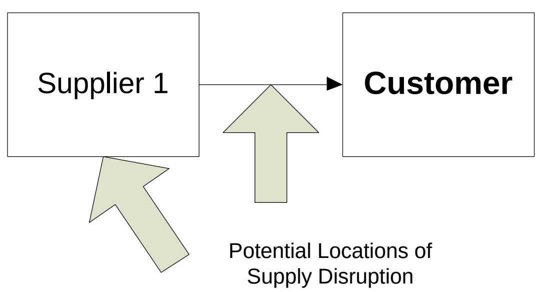

Figure 2.3 – Potential supply disruptions locations in single supplier node

Considering that there are multiple sources of disruption risks in a supply chain, conceptually there would be some amount of total supply disruption risk in a supply chain. A modification of the risk equation by Manuj, Dittman, and Gaudenzi (2007) (Equation 2-3), combined with concepts from a risk equation by (Chapman 1997) for project risk yields Equation 2-4 which indicates that the total supply disruption risk is the sum of all the losses, *L*, from individual disruption events, *n*, weighted by their probabilities, *P*. This would provide a measure of total disruption risk for a supply chain if it was possible to identify all disruption risks for a supply chain, and one could know in advance the losses from each risk event.

$$R_{\text{Supply Disruption}} = \sum\left[P_{\text{Disruption Event n}} \times (L_1 + L_2 + L_3 + \cdots + L_m)_{\text{Disruption Event n}}\right] \quad (2\text{-}4)$$

As an extension of Figure 2.3, Figure 2.4 shows a conceptual model of all of the possible locations of disruption risks in a simple supply chain. All the disruption risks at all these locations combined would be represented by Equation 2-4.

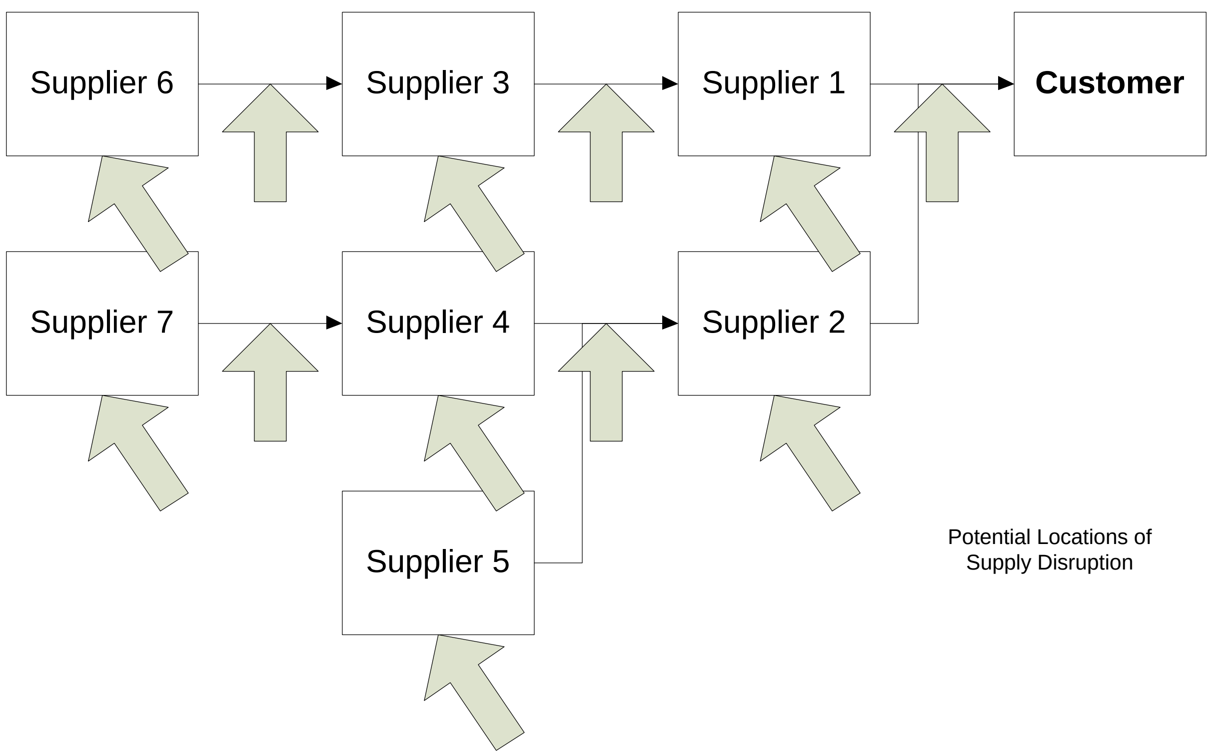

Figure 2.4 – Potential supply disruption locations in multi-node supply chain

Kleindorfer and Saad's (2005) division of risk between "normal supply-demand coordination risks," which is more aligned with RSC*Model*'s agility analysis capability, and "disruptions to normal activities" is one distinction that helps further understand supply disruption risk. The authors mention that disruption risk includes operational risks such as equipment malfunctions, unforeseen discontinuities in supply, human centered issues (such as strikes, etc.), natural hazards, terrorism, and political instability. Indeed, from the descriptions of various risks discussed in the previous section (2.1.2) we can see that supply disruptions in the supply chain could occur as a result of a number of different risks or series of various risk events that ultimately lead to a supplier being unable to produce or deliver demanded goods (or services), disrupting the flow of goods coming from that supplier. As described later, RSC*Model* is not concerned with the source of the risk but only the resulting disruption, and as such, no attempt is made here to identify all of the potential risks that can create supply disruptions. This act alone would be a significant task. Kleindorfer and Saad indicate that disruption risk has not been addressed as much in the literature as supply-demand coordination risks.

Kleindorfer and Saad also note that according to the literature and some research studies, supply managers are and should be concerned with supply disruption risk. Just as there are many conditions today making supply chain risk more prevalent, as discussed earlier, many of those and other conditions are increasing the presence of supply disruption risk in supply chains. Kleindorfer and Saad cite longer paths and shorter clock speeds as just two conditions that are creating more opportunities for disruptions and smaller margins for error if disruptions do occur. This means that disruption risk is not only more prevalent, but also brings potentially greater consequences. One industry study showed that disruption of a single supplier "causes an 11% increase in costs, 7% decline in sales growth and 35% drop in shareholder returns [over a three year period]" ("Identify and Reduce Supplier Risk" 2010). Another recent survey of industrial and consumer goods manufacturers from North America, Europe, Asia, and Latin America found that 58% of firms surveyed suffered financial losses from supply chain disruptions over the past year. Another recent report indicates that although the total number of companies reporting disruptions has declined recently, there have now been five consecutive quarters with 33% or more of companies reporting having experienced a significant supply chain disruption, requiring the engagement of an alternative supplier within the last quarter. In some cases the size and location of suppliers in the supply chain is also correlated with higher disruption risk. Disruption due to supplier failure caused by financial woes appears to be more common among smaller suppliers that are not as able to weather tough economic times as well as their larger counterparts. To compound this problem, such firms are typically at tier three or higher in the supply chain where they are often not visible to the focal firm ("Identify and Reduce Supplier Risk" 2010), which, as discussed, tends to increase risk.

2.2 Supply Chain Risk Management

The goal of risk management has always been the same, even if the approach has not been: "provide a sound basis for decisions on whether risks are acceptable and, if necessary, obtain reliable information [on] how they can be dealt with … on a consistent and reliable basis" (Purdy 2010). Risk management then is the means by which one attempts to cost-effectively balance supply chain risks and the need to achieve performance objectives. While the focus and attention given to supply chain management has been growing for some time, the specific focus on supply chain risk is relatively new. Some find that companies have been paying too much attention to traditional cost concerns in the recent past and not enough on risk to make improvements. Consulting firms, however, are noting that companies are now focusing more on understanding supply chain risks and increasing supply chain visibility, largely because of lessons learned in the recent economic downturn ("Identify and Reduce Supplier Risk" 2010).

The increased exposure to vulnerabilities from current supply chain trends in recent years has increased the attention given at all levels of management to supply chain risks which have now "taken center stage as a vital risk management priority" (Schneider 2008).

A 2011 study by BDO USA, LLP found that the largest 100 publicly traded technology companies are growing increasingly concerned with supply chain risks (Malloy 2011). Similarly, a 2010 study by ChainLink Research found that some of the top "goals, challenges, and priorities" for companies today are concerned with "building an agile supply chain and reducing risk" (McBeath 2010). The BDO USA, LLP research, which reviews SEC 10-K filings, found that 86% of these companies cited supply chain issues as a top risk factor compared to just 75% from a year earlier, putting it tied for the sixth most commonly cited risk factor. The same research found wide and increasing concern over multiple risks potentially contributing to the risk of supply chain disruption. These included concerns over equipment failure and delays (81%, up from 64%), potential disruption due to natural disasters and geopolitical issues (81%, up from 55%), credit or financial risk of customers, vendors or suppliers (61%, up from 48%), and price and availability of raw materials (34%, up from 19%).

While companies are always looking to improve the effectiveness and efficiency in their operation and management of supply chains, when it comes to managing supply disruption risk most still struggle. Despite the increased attention, Manuj, Dittman, and Gaudenzi (2007) note that "most firms [still do not] fully understand how to identify and manage the risks associated with the complex trade-offs involved in making correct global decisions" causing many managers to be hesitant in pursuing global initiatives, which becomes a problem in effective supply chain management when most supply chains today are global. ChainLink Research's 2011 supply chain risk survey found that 50% or more of surveyed companies say they are good or very good at managing supply chain risks related to “manufacturing production reliability and flexibility” and “[their] company’s own business continuity policies and practices,” which are concerned mostly with their own internal business processes (McBeath 2011b). This study found, however, that the surveyed companies rated themselves very poorly on their ability to manage risks that could lead to disruptions in the supply chain such as natural disasters, labor disputes, geopolitical issues, infrastructure failures, and poor demand forecasting.

The simple recognition of the importance of supply chain risk management is not enough for organizations to effectively manage risk. A 2007 AMR Research survey indicated that “46% of companies planned to evaluate and/or implement supply chain risk management technology in the next 12 to 24 months” (Schneider 2008), yet overall expenditures on supply chain risk management is still extremely low. A recent 2011 industry survey found that 95% of respondent companies spend less than $1 million annually on “assessing and auditing supplier and supply chain risk" with 45% spending less than $50,000 (McBeath 2011a). This same survey also found that while almost 90% of respondents said supplier risk assessment is either “frequently or always part of their supplier selection process,” almost 40% said they rarely conduct risk assessments for even their most critical suppliers. Additionally, the survey found that the responsibility for supply chain risk assessment in most companies still falls on low-level managers "with immediate responsibility for operational functions as well as the head of those functional units, such as the VP of supply chain," with fewer than 20% of companies assigning supply chain risk management responsibilities at the executive level.

The discipline of risk management is still an “emerging” and rapidly expanding area that needs further development and understanding of generalizable approaches for better management. Proctor and Smith (2010) explain that “a deeper and common understanding of how risk events affect business performance is needed" since “improperly managed risk can lead to business failures and poor business performance." This creates a situation where "the benefits of many operational risk management activities are not clear to the business people," which reduces the ability to make better business decisions about risk and ultimately makes it difficult to promote and support risk management activities that lead to cost savings. Further, there are extra conditions that make risk management in supply chains more difficult than other management activities. All supply chain members have a bearing on management of supply chain risks, not just individual firms (Faisal, Banwet, and Shankar 2006), and risks can originate in multiple places including internally as well as externally at any location in the chain. These interdependencies can make supply chain risk management especially difficult.

Faisal, Banwet, and Shankar indicate that the key issues in supply chain management are the formation (i.e. configuration) and efficient coordination of the supply chain, both of which relate to the creation of the various interdependencies in supply chains. An important component in the effort to improve the management of disruption risk is the use and development of tools and methods to aid in making decisions about these types of issues. There are many different tools and methods available and others in development for managing risk in supply chains, however, a review of a sample set of some of these tools in Section 2.5 shows that the effectiveness and suitability of different approaches varies.

Several authors provide guidelines for improving the effectiveness of risk management efforts. The ISO 31000 risk management standard, as outlined by Purdy (2010) identifies eleven principles, or performance criteria that an effective risk management approach should possess. According to the standard, effective risk management should:

1. Create and protect value
2. Be an integral part of all organizational processes

3. Be part of decision making (including playing a central role in the organization's management process)
4. Explicitly address uncertainty (decision making should explicitly consider risk)
5. Be systematic, structured, and timely (including fully defined and accepted accountability for risks, controls, and treatment tasks)
6. Be based on the best available information (which should be facilitated through continual communication and reporting of risk management performance among internal and external stakeholders)
7. Be tailored
8. Take into account human and cultural factors
9. Be transparent and inclusive
10. Be dynamic, iterative, and responsive to change
11. Facilitate continual improvement of the organization (including setting organization performance goals and measurements)

Additionally, it is implied that principles 3, 4, 5, 6, and 11, and accompanying concepts, provide evidence when present that an organization has a "current, correct, and comprehensive understanding of risk." Purdy explains that achieving these principles and the necessary amount of integration into business processes appears straight forward but in reality is a major struggle for many organizations since "introducing soundly based risk management usually requires alignment with and even changes to the organization's culture and processes." Because of this, Purdy notes that "more of the [ISO] standard is concerned with the implementation of risk management than with the process."

Schneider (2008) also identifies three key objective for an effective supply chain risk management strategy: (1) identify and prioritize critical business elements, (2) map the entire supply chain to show interdependencies, and (3) identify potential failure points along the supply chain. He also notes that while traditional risk management efforts have focused on identifying and evaluating risks and potential consequences by examining the various supply chain components, this alone does not provide a "fully comprehensive supply chain risk management plan." From Schneider's point of view, a fully comprehensive plan needs to continually engage both senior management and functional supply chain managers as active participants in the process. A common theme throughout the literature on effective supply chain risk management is the necessity of involving upper management in the process and the use of cross-functional teams (Zsidisin et al. 2004). This is indicated as an effective way to help ensure adequate focus, attention, and resource allocation, and also to improve risk identification, evaluation, and strategy implementation.

Kleindorfer and Saad (2005) also outline from their literature review and research ten principles that should be implemented simultaneously and integrated with disruption risk management efforts. First, it is imperative that your own house is in order with appropriate risk management processes first before expecting others in the supply chain to do so. The implication indicated here by the authors is that supply chain risk management requires management of three main supply chain network subsystems: supplier relationship management (SRM), Internal Supply Chain Management (ISCM) which includes internal facility management to identify and mitigate disruption risks and senior management commitment to the process, and Customer Relationship Management (CRM). Second, principles of portfolio theory from finance to reduce risk; in particular, diversification of facility locations, sourcing options, logistics (transportation modes) and operational modes. Third, "robustness to disruption risks in a supply chain is determined by the weakest link in the chain" and therefore incentive alignment, vulnerabilities identification and assessment, and testing of response systems throughout the supply chain are important. Fourth, “prevention is better than cure.” Risk avoidance measures are preferable, and when avoidance is not possible pre-disruption mitigation efforts are still likely to be less costly than post-risk recovery, although contingency plans remain important. Fifth, Lean and other efficiency efforts may increase vulnerability to risks at firm and supply chain levels as the trade-off between robustness and overall efficiency of normal operations is often ignored. Sixth, as a corollary to the last principle, backup systems (redundancies), contingency plans, and reasonable slack in production and operations planning can increase the level of readiness to manage risk. Seventh, sharing information and best practices both internally and among supply chain partners is essential to improve risk identification and effective execution of crisis management plans and approaches. Eight, good crisis management skills are insufficient; risk assessment and quantification as part of on-going process management using probabilistic measures are essential *before* disruptions occur to ensure mitigation efforts are the most cost-effective. Ninth, modularity in product and process design not only increase agility and flexibility aiding to create lean supply chains, it also improves supply chain resiliency by increasing flexibility and mobility of resources which reduces risk and improves response speed for contingencies. Tenth, quality management programs such as Total Quality Management (TQM) and Six Sigma help to improve supply chain security and reduce disruptive risks while simultaneously aiding to reduce costs.

2.3 The Risk Management Process

Multiple authors present different risk management models as structured approaches for dealing with risk in supply chains. Having an effective risk management approach appears especially important for managing disruption risk. One report indicates that those manufacturers with best-in-class risk management procedures in place are twice as likely to have no major impact from supply chain disruptions ("Identify and Reduce Supplier Risk" 2010). Hubbard's (2009) definition of risk management, "the identification, assessment, and prioritization of risks followed by coordinated and economical application of resources to minimize, monitor, and control the probability and/or impact of unfortunate events," outlines the typical steps of a risk management model.

The ISO 31000:2009 risk management standard also outlines a risk management process. The standard was developed to support a new, simple, and unified way of thinking about, approaching, and defining risk as well as provide a risk management process that offers a consistent and reliable method for managing all forms of risk. The ISO risk management model is represented in diagram form as shown in Figure 2.5.

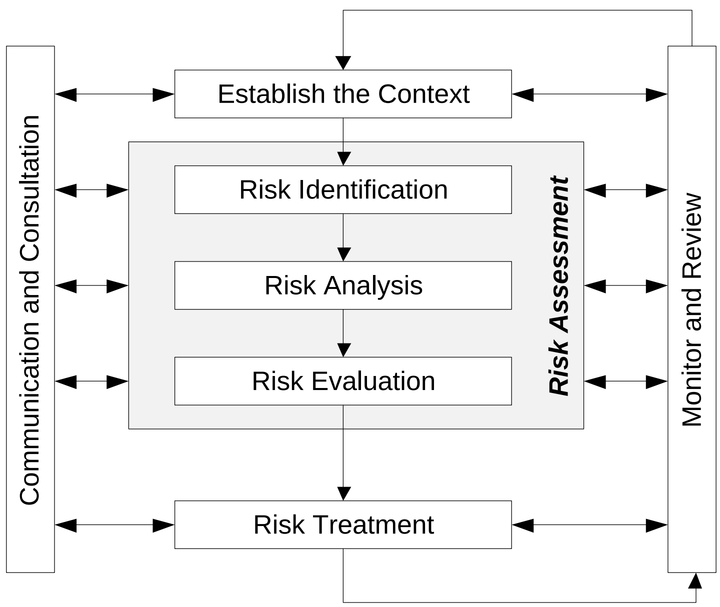

Figure 2.5 – The risk management process from ISO 31000

In the simplest form, the ISO risk management model is made up of 4 primary steps: establish the context (of the risk management effort), risk assessment, risk treatment, and monitor and review (the process). Risk assessment is divided into 3 phases: risk identification, risk analysis, and risk evaluation. Communication and consultation is also indicated as an important auxiliary process for other steps in the model. Ultimately, the ISO standard describes risk management as a "process of optimization that makes the achievement of objectives more likely" (Purdy 2010).

Campbell (2004) presents a simpler, basic four step cycle for risk management, acknowledging that disagreements as to the scope, terminology, and categorization of risk management exists among various authors. Campbell's basic model is presented in diagram form in Figure 2.6. Campbell limits the risk management process to four main steps: risk identification, risk assessment, risk handling, and risk monitoring. In addition to these steps, Campbell also discusses the formulation and execution of risk mitigation and contingency plans as part of the risk handling step.

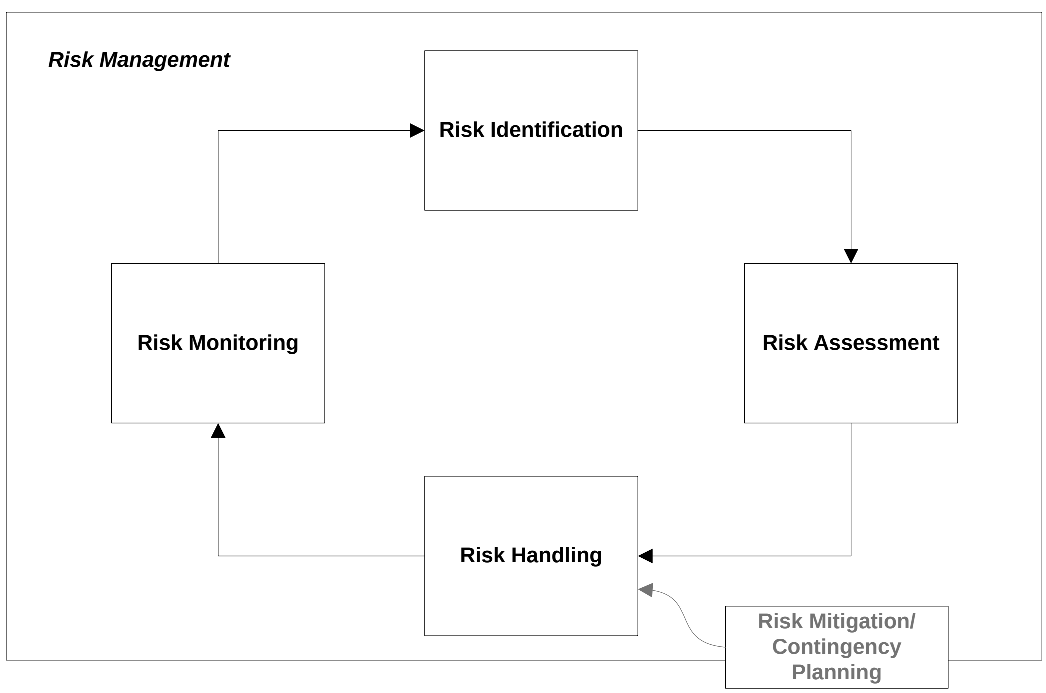

Figure 2.6 – Simple risk management process developed from Campbell (2004)

Manuj, Dittman, and Gaudenzi (2007) present a five step supply chain risk management process model based on knowledge and practices of other risk management perspectives including Enterprise Risk Management (ERM), Integrated Risk Management (IRM), and Business Continuity and Crisis Management (BCCM). ERM attempts to apply traditional financial risk management tools and methods to risk management efforts of other functional groups such as operations and supply chain management to provide an enterprise wide approach. IRM integrates three business processes of strategic management, risk management, and operations management. Since the model presented by Manuj, Dittman, and Gaudenzi incorporates concepts from ERM and IRM, they will not be reviewed in more depth here. Business continuity planning is briefly discussed elsewhere in this literature review. A diagram of the five step risk management and mitigation model presented by the authors is provided in Figure 2.7. Step one of the process is "identifying and profiling risks." It is implied in the explanation offered for this step that another activity similar to ISO's "establish context" step must also take place, the concept being that the objectives of the supply chain must guide which risks are considered in the process. Step two involves "assessing and evaluating risks" identified and profiled in step one. Step three is the development of "risk management strategies" for dealing with the risks. Step four is "implementing risk management strategies," and step five is "mitigating risks."

Chapman (1997) provides another view. He puts forth that, fundamentally, risk management is as simple as a three part risk analysis process comprised of risk identification, probability assessment, and impact estimate. Kleindorfer and Saad (2005) outline research specifically on supply chain disruption risk management and what they identify as two "joint activities of risk assessment and risk mitigation that are fundamental to disruption risk

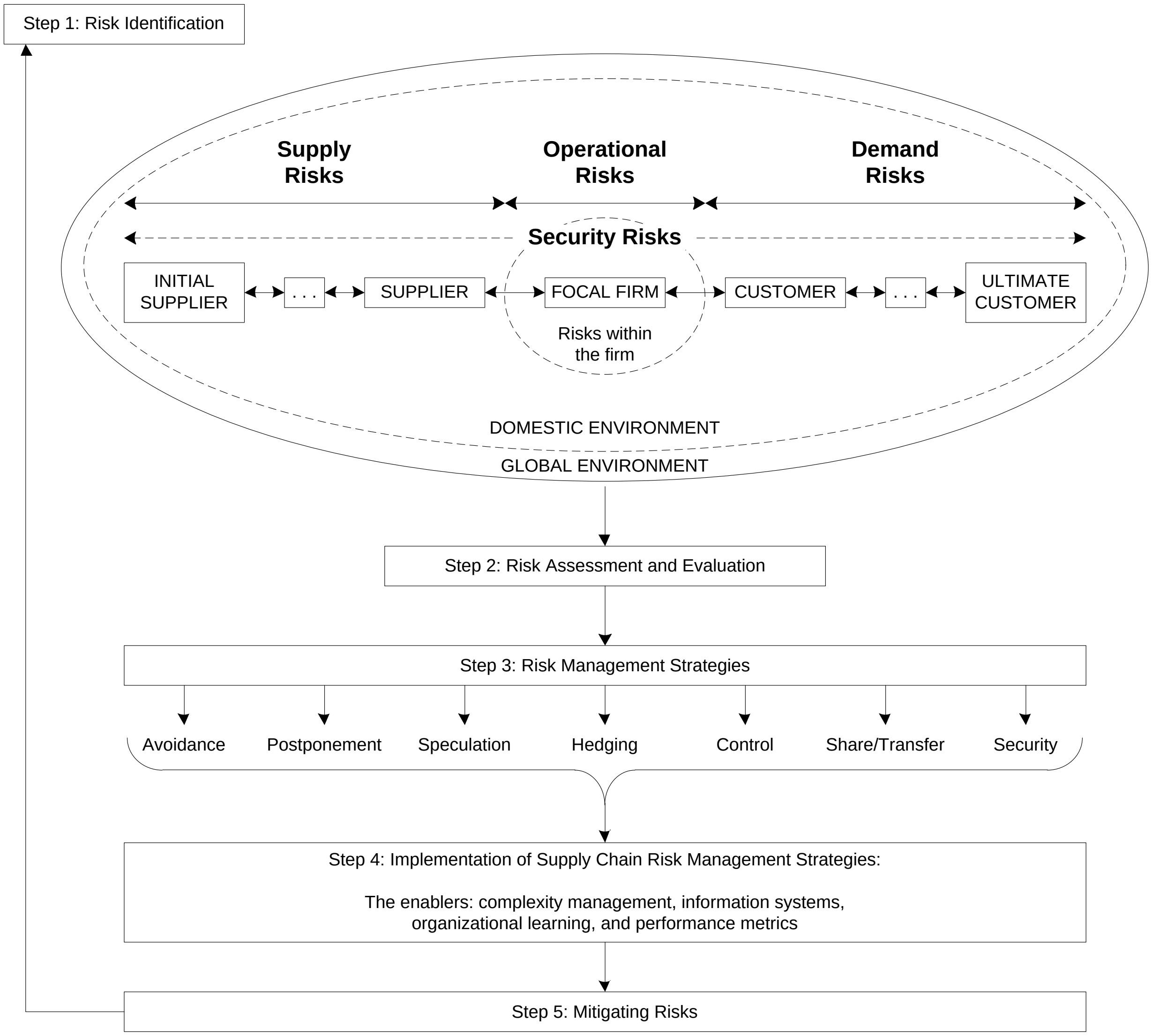

Figure 2.7 – Global supply chain risk management and mitigation framework from Manuj, Dittman, and Gaudenzi (2007)

management in supply chains." In their research on supply chain disruption risk management they also identify four main premises for effective risk management that they derive from industrial risk management theories and practices. First, to manage risk, you have to "specify the nature of the underlying hazard giving rise to the risk." Second, risks have to be quantified through a disciplined risk assessment process, and the "pathways by which such risks may be triggered" must be determined. Third, the approach "must fit the characteristics and needs of the decision environment" such that different approaches for assessment and design are needed for different supply chain environments, which is similar to the ISO step of "establish the context. Fourth, management policies and actions must be integrated with on-going risk assessment and coordination efforts among supply chain partners, implying the need for alignment between risk management efforts and other business management efforts. This is similar to the ISO "communication and consultation" step. Based on the two activities and these main premises, the authors identify three main tasks as the foundation for disruption risk management: specify, assess, and mitigate (SAM). This SAM framework deals with (1) a process to specify risk sources and vulnerabilities, (2) assessment of identified risks, and (3) mitigation of those risks. Kleindorfer and Saad also identify a four phase disruption risk management approach from the Wharton Risk Center which includes: (1) attaining understanding and approval from senior management, and assignment of process responsibilities, (2) identifying key processes, facilities, and assets that may be vulnerable to disruptions, (3) utilizing traditional risk management techniques for key processes to identify vulnerabilities, risk triggers, likelihood for vulnerabilities, and mitigation and risk transfer activities, and (4) executing reporting, auditing, legal reviews, and other management tasks.

As can be seen from the overviews of different risk management processes, one challenge with understanding risk management is the many different terms used and the different meanings in the use of each term. However, even though each of these approaches has slight differences, most follow the same basic pattern with similar steps, even if those steps are referred to by different names. It is not the purpose of this thesis to identify the best or most appropriate set of terms or definitions for risk management, but to explore and identify the basic set of steps and principles recommended in the literature for effective risk management that will allow for an evaluation of the RSC*Model* tool. From this review of various proposed risk management processes, there appears to be consensus on four basic steps for effective supply chain risk management: risk identification, risk assessment, risk treatment/handling, and risk monitoring. This is essentially the process represented in Figure 2.6.

2.3.1 Risk Identification

The first basic step for supply chain risk management is an obvious and common theme in the literature. Risk identification is mentioned in some form in all the risk management models reviewed (Campbell 2004; Chapman 1997; Kleindorfer and Saad 2005; Manuj, Dittman, and Gaudenzi 2007; Purdy 2010). (Although most authors represent the risk management process as a continuous loop with no real end or beginning, risk identification is still generally implied to be one of the first steps.) To manage a risk, you need to understand what that risk is. Risk identification is the basic process by which one determines “what uncertain future events are possible” (Campbell 2004). Understanding what uncertain future events are possible, according to the ISO 31000:2009 standard and Purdy (2010) "requires the application of a systematic process to understand what could happen, how, when, and why.” Some authors note a required step before risk identification, such as the ISO standard which indicates the preceding step of “establish the context” which consists of defining the organization’s supply chain objectives and what “external factors … may influence success in achieving those objectives” as well as identifying stakeholders. Manuj, Dittman, and Gaudenzi (2007) identify “risk identification” as the first step in the process, but from Figure 2.7, they also indicate the need to establish the “environment” in which the process is to be performed. Some other authors do not explicitly include such a step in the process; however, it is often implied for all the reasons which were already discussed about the need to properly define the type of risk one is trying to manage.

Authors in the literature make different suggestions on ways to best identify risks in the supply chain. As mentioned previously, a common recommendation in the literature is the use of cross-functional teams in the risk management process to improve risk identification through the combination of varying viewpoints and perspectives. Another suggestion is to categorize the supply chain into five networks or “sub-chains” to help identify uncertainties, or risks, and the effect they have on the business as a whole (Cavinato 2004). Failures in the sub processes of each sub-chain can then be identified as a focus is placed on examining the individual network business processes. The first sub-chain is “physical” which includes traditional logistics processes involving movement and storage of physical goods and associated processes such as transportation. The second is “financial” and includes business processes related to cash flows, accounts receivable, accounts payable, expenditures, etc. The third sub-chain suggested is “informational” which encompasses information access, electronic systems and data movement, market intelligence, etc. The fourth is “relational” which represents the processes relating to creating and maintaining supply relationships and supply chain configuration. The fifth is “innovational” and is concerned with the processes and linkages for discovering and developing new products, services, and processes.

As mentioned previously, poor supply chain visibility is a problem for many companies and inhibits risk identification. When suppliers beyond the first or second tier are unknown to the focal firm it cannot be expected that risks posed by those suppliers will be known. One recent industry report ("Best Practices for Supply Chain Improvement" 2011) indicates that supply chain visibility will climb on the IT application priority list in the near future as use cases are identified where it can increase cost savings and improve service levels. One of those important use cases appears to be for risk identification. According to another report ("Identify and Reduce

Supplier Risk" 2010) gaining supply chain visibility is usually a very difficult, manual, and expensive process. One reason for this, presumably, is that according to this report it isn’t sufficient to look at supplier financials alone to assess supply risks. Therefore, while publicly available financial data may be easy to obtain and analyze, it doesn’t provide sufficient information to identify all supply disruption risks. According to this report, efforts should focus on identifying the suppliers “whose problems could affect the business most” with a focus beyond just financials. Monitoring compliance with environmental and legal issues is also necessary. The report suggests the creation and use of a dashboard with multiple warnings signs for suppliers with data from multiple sources to improve supply chain visibility and risk identification for suppliers in the chain.

In identifying risks, you can simply attempt to identify the potential problems or failures, the potential risk event, and the potential consequences or you can focus on determining the root cause of those problems. As discussed, part of many discussions in the literature about risk identification involves the need to identify risk “triggers” or the sources/root causes of potential risk events. This concept is very applicable to identification of disruption risks. Some authors identify (Zsidisin et al. 2004) and recommend (Manuj, Dittman, and Gaudenzi 2007) the use of principles and processes similar to the Failure Mode and Effect Analysis (FMEA) methodology used in quality and product design to identify such risk causes or “triggers” and the associated consequences that may result.

Risk identification can ultimately, however, been a difficult process. A recent industry week report mention earlier ("Best Practices for Supply Chain Improvement" 2011) found that the past is no longer sufficient to plan for what might occur in the future, citing that two-thirds of respondents to a recent industry survey “predict more future risk [for supply chains] than they did just a year or two ago." Companies today must now plan for future uncertainties in supply chains and cannot rely on past events and data to tell them what is possible in the future.

2.3.2 Risk Assessment

Detecting risks is part of the first step of risk identification, and risk assessment, where one seeks to more fully understand the risk, is the second general step for risk management discussed in the literature. Appropriate methods to not only identify but also assess risk can help organizations make informed decisions about risk. The ISO standard calls this risk analysis and risk evaluation while Campbell and Manuj, Dittman, and Gaudenzi refer to this step as "risk assessment" and "risk assessment and evaluation" respectively. Kleindorfer and Saad's (2005) SAM framework identifies "risk assessment" as a primary step. Purdy (2010) and Zsidisin (2004) argue that understanding supply risks is critical to success and the better one is at detecting and understanding risk, how it is caused and influenced, the more effectively one can change it to achieve the desired objectives, and potentially achieve those objectives "faster, more efficiently, and with improved results."

The exercise of quantifying risk is often stated or implied as part of this step. Zsidisin et al. (2004) argue you need to know both the probability and loss to understand the significance of a risk event. As described previously, Fischhoff, Watson, and Hope (1984) explain that analyzing a risk and determining how "risky" it is depends on the definition used for risk and there needs to be "some quantitative summary … expressing how much [there is] of that kind of risk." Fischhoff, Watson, and Hope also make the point in their 1984 article that "definitive estimates of both the *magnitude* and *importance of …* consequences" would be needed to make a definitive statement regarding risk (emphasis added). Risk quantification, however, is difficult and there are many different approaches to attempt to quantify the probability and expected consequences of a risk event. By definition risk involves a future event so risk quantification inevitably involves forecasting which is always fraught with errors.

Kleindorfer and Saad suggest the use of probabilistic assessment using tools such as fault and event trees to analyze and evaluate risks. Zsidisin et al (2004) identify two options for the risk assessment phase of risk management: (1) firms can proactively assess the probability and impact of supply risk in advance, or (2) firms can reactively discover risks after a detrimental event occurs. According to Kleindorfer and Saad's eighth step for effective risk management, the prior option is preferred from a cost standpoint. Zsidisin et al. completed a study of the risk management processes and efforts of seven companies and a review of different risk assessment approaches and found two common themes. First, all risk assessment techniques reviewed included procedures to investigate the probability and impact of detrimental events that occur with inbound supply. A second commonality to the approaches was the use of techniques for obtaining risk information associated with suppliers or the supply market. The study also found that out of seven companies, two companies had formal risk assessment techniques and processes in place, while the remaining five firms did not have specific, stand-alone risk assessment processes established "but instead use a variety of proactive supply management techniques to assess supply risk."

Zsidisin et al. suggest facilitating obtainment of information to verify supplier behavior for improved risk assessment. They also suggest that a major part of assessing supply risk involves identifying the likelihood of occurrence of a risk event, the stage in the product life cycle, extent of likely loss, exposure to loss of focal firm, and likely triggers of the risk event. Like risk identification, cross-functional teams are a commonly suggested method for improving risk assessment. Zsidisin et al. suggest the use of cross-functional teams to quantify the size of potential problems and their effect on profitability and also outline a suggested conceptual approach for risk assessment from Steele and Court (1996) consisting of three steps: (1) determine probability of risk event, (2) estimate likely problem duration, and (3) investigate business impact of risk event. The authors assert that traditionally risk assessment has been seen as just a proactive approach, but argue that their research indicates it may also occur as "a secondary benefit of the implementation of proactive supply management tools" such as those focused on quality, supplier performance improvement, and supply interruption prevention. In their study the authors identify six quality tools used to assess risk: Malcom Baldridge National Quality Award, supplier interlock matrices, supplier scorecards, supplier self-assessments, designated and certified quality representatives, and supplier self-release audits. Zsidisin et al. find that risk assessment should only be one step in the overall risk management strategy of a firm and that costly programs specifically to assess supply risk are often not needed. The focus, they indicate, should simply be on providing early warning indicators of potential supply problems. Ultimately, there is a trade-off associated with the time and cost to gather extra information for more accurate risk assessment.

Risk assessment, as indicated is generally discussed as focusing on identifying probability and potential consequences. These measures combined, as in the general risk equation, can provide a quantified measure of risk that can be used to prioritize and rank risks and determine which risks are acceptable and which risks need to be further addressed in the next risk management step. Some authors seem to imply that risk only exists when “there is a relatively high likelihood” or high probability of “a detrimental event” and “that event has a significant associated impact” (Zsidisin et al. 2004). This still aligns with the conditions of uncertainty and consequence, but according to arguments of other authors this would be a condition to classify something as a high risk but not exclude it from being a risk at all. Chapman suggests taking probability assessment values and impact estimates, in hours or dollars for a disruption event, and then multiplying them to provide a risk score to quantitatively characterize a level of risk. In this approach, however, some problems emerge with the characterization of potential consequences and units used. Campbell states, as an example, to "estimate the impact in hours or dollars if the event occurs." As indicated with the three steps for risk assessment by Steele and Court, a problem with this assessment is that it is mixing the potential duration of an event with the potential impact. For example, if the risk is a strike that lasts 30 hours, that is the duration or "magnitude," but that doesn't tell you what the impact is on the business such as cost, how many sales were lost, etc. The suggestion that the impact can simply be estimated in either hours *or* dollars presents a shortcoming in such methods that will be addressed in more detail in Chapter 4 with the presentation of a more comprehensive view of risk.

The topic of risk assessment and the effort to determine the probability and (i.e. consequences) introduces an argument in the literature against many of these efforts. McBeath (2011b) argues that a major flaw in disaster planning is the focus "on potential events and their probability rather than on assets and impacts." The concept of Black Swan events was created by Nassim Taleb and they are characterized as "low-probability, high-impact events that are almost impossible to forecast" (Taleb, Goldstein, and Spitznagel 2009). The idea presented with Black Swan events is that sometimes you can't assess beforehand what the likelihood or impact of an event might be. Geopolitical and natural disasters, which represent very plausible sources of supply disruption risk, have been characterized as Black Swan type events that are very difficult to manage precisely because of this limitation (McBeath 2011b). According to Taleb, Goldstein, and Spitznagel Black Swan events are "increasingly dominating the environment" because, as mentioned previously, globalization has created complexity of relationships and interdependencies and “complexity makes forecasting even ordinary events impossible.” One of corresponding lessons from Black Swan events concerning risk assessment is the inability to predict the future for such events based on the past. As a previously mentioned report ("Best Practices for Supply Chain Improvement" 2011) indicated, many companies expect more risk in the future than they have experienced in the past. In the case of Black Swan events, hindsight is not foresight as, according to Taleb, Goldstein, and Spitznagel, “past events don’t bear any relation to future shocks” as “today’s world doesn’t resemble the past.” The authors make the argument that the world, including supply chains, are more complex and interdependencies are greater now than in the past. As discussed earlier, to fully understand a risk “we have to predict both an event (the probability of risk) and its magnitude, which is tough because impacts aren’t typical in complex systems.”

Another corresponding argument made by the authors then is that “risk management … should be about lessening the impact of what we don’t understand – not a futile attempt to develop sophisticated techniques and stories that perpetuate our illusions of being able to understand and predict the social and economic environment.” This does not mean however that risk assessment has no role in dealing with Black Swan events. The proposed risk assessment goal has simply changed. “Instead of trying to anticipate low-probability, high-impact events, we should reduce our vulnerability to them.” The argument for Black Swan events is that risk assessment should focus on the consequences or impact and not the probability of the event. “It’s more effective to focus on the consequences – that is, to evaluate the possible impact of extreme events.” Often this concept is misconstrued. Grackin (2011) suggests that often people think that since low-probability, high-impact events are not predictable they shouldn’t bother doing anything about them. However, one should not discount events just because they are rare. Instead, the argument is that models should be built with the premise that something will go wrong, regardless of source. Taleb, Goldstein, and Spitznagel go on to make the case that “in companies, redundancy consists of apparent inefficiency: idle capacities, unused parts, and money that isn’t put to work,” but, as discussed previously, this leaves little resiliency in the supply chain to handle disruptions. The basic implication from the Black Swan argument is that while there may be lots of good ways and reasons to attempt to eliminate the sources of risk, that is not always possible, and in the end what you really need to be good at reducing the effects of risk. Sometimes you can focus on identifying the root causes, but that is not always possible and, as mentioned earlier you often don’t have a whole lot of control over those causes especially from the customer standpoint.

One additional important concept presented by Campbell (2004) is that risk management “must be able to distinguish between handling of certain future events and the handling of uncertain future events.” Based on the previous discussion of risk, it is only uncertain future events that pose a risk. If an event is certain then it is a known problem and the method to manage is going to be different.

2.3.3 Risk Treatment/Handling

The third basic phase of risk handling identified in the literature is that of risk treatment or risk handling. This step is the focal point of the entire risk management process as it deals with actually addressing the problems that unacceptable risks, as identified in the prior step, have on the supply chain objectives. Faisal, Banwet, and Shankar (2006) state that the risk management process “is focused on understanding the risks and minimizing their impact by addressing, [for example,] probability and direct impact." According to Campbell, "risk handling is the activity in which risk mitigation strategies and contingency plans are formulated and put into practice." From the ISO standard point of view risk treatment is concerned with changing the magnitude and likelihood of consequences to achieve a net increase in benefit which "involves the evaluation of and selection from options, including analysis of costs and benefits and assessment of new risks that might be generated by each option, and then prioritizing and implementing the selected treatment through a planned process."

Part of risk treatment is the formation, implementation and execution of risk mitigation plans. For unacceptable, unidentifiable, or unquantifiable risks, the goal is to reduce the impact on the supply chain and the business as much as possible. As discussed previously, "controls" are described as a mechanism to avoid a risk event by reducing the probability and "mitigants" as a mechanism to avoid the consequence or impact of a risk event. The ISO standard reviewed by Purdy simply indicates that controls are the outcomes of risk treatments whose purpose is to simply modify risk, which implies changing either the probability of occurrence *or* the consequences of the risk event. Although alternative terms may be used by different authors the idea is still the same for risk treatment and handling. In this thesis risk mitigation is used to encompass the concepts of contingency plans, risk mitigants, and controls. In risk assessment you try to determine the probability and impact, and in risk treatment you try to reduce one or both of them and there are several options for doing that.

Chapman (1997) indicates that "one way to reduce risk is to gather information about relevant issues to lower the level of uncertainty" or simply to "have less ambitious goals" to change the objectives such that the risk is reduced. The ISO 31000 standard provides a general set of "risk treatment" options, list from most to least preferred:

1. Avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk

2. Taking or increasing the risk in order to pursue an opportunity
3. Removing the risk source
4. Changing the likelihood
5. Changing the consequences
6. Sharing the risk with another party or parties (risk transfer, insurance, risk financing, etc.)
7. Retaining the risk by informed decision

Step three in the Wharton Risk Center model discussed by Kleindorfer and Saad, mentions the use of “risk transfer activities” as part of traditional risk management techniques, which is essentially the same thing as item six from the ISO standard above. Risk transfer is discussed in the literature by several authors as a method to transfer at least a portion of the impact or cost of a risk event to another party, which is typically done through insurance. Based on the supply chain risk categorization by Schneider (2008) presented in the earlier discussion of supply chain risk areas, supply disruption risk is considered to be primarily a "traditional" or "insurable" risk, as supplier failure and continuity of supply capture the basic risk areas that lead to a disruption. This indicates that at least some hold the view that supply disruption risk can generally be handled through methods of risk transfer, such as traditional insurance. The concept of risk transfer, however, is ultimately not at the focus of this thesis.

An industry best practices report indicates that ("Identify and Reduce Supplier Risk" 2010) once key suppliers “whose problems could affect the business most” are identified in prior steps, the suppliers should be engaged to assess risks, and an alternative supplier should be identified if necessary. Continuity plans are a related topic often discussed with risk treatment. Purdy (2010) explains that risk management is part of business continuity planning (BCP), but BCP goes beyond risk management by assuming the risk will happen. Essentially, in continuity planning potential risk events are assumed to happen at some point in the future and plans are made about how to best deal with the consequences of that event. For Black Swan type events, continuity planning is an important process.

A study by Tomlin (2006) identified and studied the effects of several possible disruption management strategies: carrying inventory, single-source from reliable supplier, multi-sourcing, passive acceptance, and contingent rerouting. In the study Tomlin found that the optimal management strategy to deal with disruption risk depends on the nature of the disruption, including its length and frequency, and the supply chain and supplier conditions. Under different scenarios each of these strategies, or a mixture of them, could be the ideal approach.

A recent Gartner consulting report states that "traditional risk management sometimes focuses only on minimizing threats through the use of controls" but argues that many threats, like earthquakes, are not controllable and it does little good to measure them (Proctor and Smith 2010). Instead, the authors argue that companies should focus on things that are controllable like their own business continuity management plans and suggest developing and using Key Risk Indicators (KRIs) and Key Performance Indicators (KPIs) to create causal chains linking risks to impact. Manuj, Dittman, and Gaudenzi also suggest that risk “triggers” are often beyond the control of any single entity, implying that it is not always practical or possible to try to alter or eliminate the root causes of problems.

As a result of their study, Faisal, Banwet, and Shankar (2006) present a preliminary hierarchical model of the relationships among eleven supply chain risk mitigation enablers, or variables that enable risk mitigation through reduction of the probability of consequence of various supply chain risks. Such a hierarchy could help distinguish dependent from independent enablers and their relationships to know how to better minimize risks. The result of their study for the eleven mitigation enablers is graphically represented in Figure 2.8.

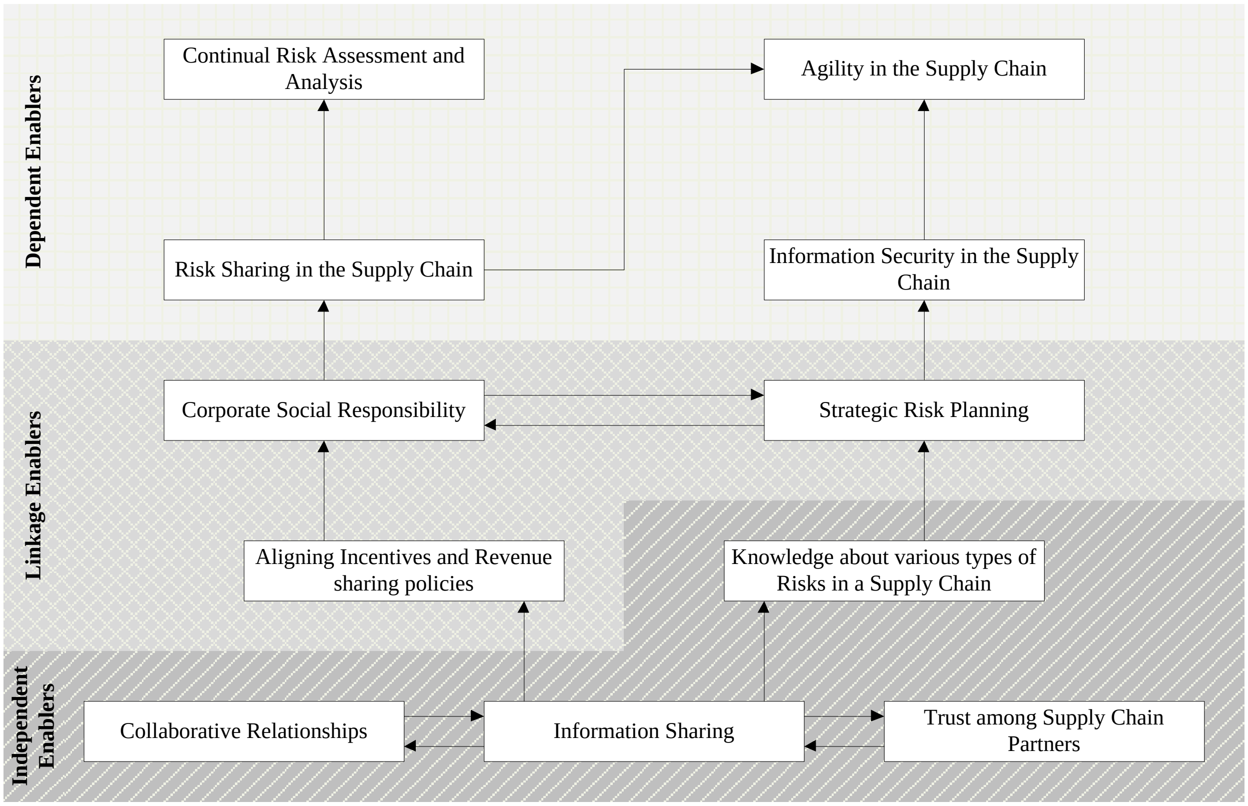

Figure 2.8 – Hierarchy of eleven risk mitigation enablers adapted from Faisal, Banwet, and Shankar (2006)

Ultimately, some disruption risks in the supply chain will be accepted or otherwise ignored and mitigation strategies will not be actively developed to handle the risk. An additional important concept relating to a way to deal with these types of risk and to generally reduce the exposure to risk occurrence and consequences is to create resilience and security in the supply chain. Melnyk et al. (2010) describe that the objective of supply chain resilience is to “develop a system that can identify, monitor and reduce supply chain risks and disruptions, as well as react quickly and cost-effectively." Resiliency can be created in supply chains through purposeful design, including configuration and coordination decisions. Similarly, security can be created through purposeful design of the supply chain that limits the possibility of disruption due to external security threats. Melnyk et al. identified several design traits that can increase resiliency and security including: reduced slack and increased redundancy in inventory, lead time, and capacity, standardized products and processes, reduce waste and variance, modular design (each tier manages their own suppliers), pre-certify suppliers, and in the case of security limit the number of suppliers. In the case of sourcing, there can be a conflict with resiliency and security, with one favoring multi-sourcing and the other single sourcing. Pre-certification of suppliers is one way to balance the two. They also indicate the focus needs to be not only on suppliers but also logistics.

2.3.4 Risk Monitoring

The fourth basic step of risk management addressed in the literature is that of risk monitoring. According to Campbell, "risk monitoring is the activity that assesses the effectiveness of the risk mitigation strategies and contingency plans. Risk monitoring is the activity that determines when overall risk is reduced because of the implementation of risk management plans or because risk events have not occurred." Purdy explains the purpose of the risk monitoring step in the ISO standard is to ensure that "appropriate action occurs as new risks emerge and existing risks change as a result of changes in either organization's objectives or the internal and external environment in which they are pursued" which involves environmental scanning, control assurance, broad view, and learning lessons about risks and controls. Risk monitoring is essentially the step to evaluate the effectiveness of the other steps and to complete the loop in the risk management process.

2.3.5 Total Cost of Ownership

The quality guru W. Edwards Deming promoted the idea in his 14 points for management that contracts should not be awarded based on price tag alone (Foster 2010) since the initial price offered by suppliers is rarely enough information to tell you what the real total cost of a product will be when taking into account quality, reliability, maintenance, risk and other costs (Ellram 1995; Ellram and Siferd 1993; Ferrin and Plank 2002). In the purchasing realm of supply chain management this total cost is typically referred to as the Total Cost of Ownership (TCO), or in some cases Total Ownership Cost (TOC). In short, TCO is traditionally considered as the sum of all costs associated with the research, development, procurement, personnel, training, operation, logistical support and disposal of an individual asset (Josiah 2002) with the goal of "understanding the true cost of buying a particular good or service from a particular supplier" (Ellram 1995). The concept of TCO has been around in some form since at least the early 1980s and has been studied and promoted in the supply management (purchasing) discipline over the past few decades as an effective way to look at the real total cost of product procurement by looking beyond initial purchase price (Ferrin and Plank 2002).

The traditional view of TCO indicates that the concept has typically been applied to sourcing decisions from individual firms. Today's companies, however, source many components from many suppliers in increasingly complex supply chains. Simply going for the lowest price can often result in greater overall supply chain costs and ineffective and uncompetitive supply chains. Ferrin and Plank note that Joseph Cavinato suggested as early as 1991 the need for a value-based, multi-firm, or supply chain level approach to TCO.

They also suggest that such a supply chain approach would be similar to the traditional single-firm approach. From such a supply chain perspective, TCO could be viewed as a holistic measurement of all supply chain related activity and procurement costs, including both direct and indirect costs, incurred through execution of a supply strategy.

Ferrin and Plank note the application of TCO to supply chains has been limited. They found that leading-edge companies are applying TCO concepts but many firms are still struggling in their attempts to use TCO valuation logic even in traditional supply management applications. They indicate that while a broader application of TCO to the supply chain as a whole is desirable, “little research exists on this approach.” One problem they note is that there are a vast number of cost drivers that could be tracked and used to evaluate TCO, and while many are universal, there is not likely to be one standard TCO valuation model that works for all situations. This is likely to be even more the case when applied on a broader supply chain scale. The implication then is that no standard approach is likely to exist for measuring TCO of every supply chain. To apply TCO to a supply chain model then, an important step is to determine which cost drivers are most appropriate to include in TCO calculations so they can be tracked and minimized. A supply chain model designed to measure TCO of a supply chain may also need to be flexible in defining which costs are tracked and reported.

Minimizing TCO of supply chains is seen as increasingly important when looking at supply chains specifically with respect to disruption risk. McBeath (2004) argues that effective risk management can dramatically improve a company’s performance through lower total cost and higher service levels “compared to traditional approaches that don’t adjust well to unpredicted events.” There are consequences, including a cost, associated with the risk of supply disruption in the supply chain, even if the risk event never actually occurs (Fischhoff, Watson, and Hope 1984), and if supply chains are not designed to reflect the cost and other consequences then total costs are likely to increase and customer needs will not be met. Ferrin and Plank note Cavinato also arguing “that firms can reduce their total supply chain costs by assigning specific supply chain processes to those firms in the supply chain whose cost structures are optimally configured to support the assigned processes." Extending this logic to the management of supply chain risk suggests that most risk mitigation strategies should attempt to optimize supply chain configuration, coordination, and procurement decisions such that supply chain costs associated with risks are minimized. The risk management question then becomes not just how to mitigate the most risk, but how to mitigate risk in such a way that minimizes the total ownership cost of the supply chain. This ultimately leads to more complicated supply chain management decisions. In the case of disruption risk management, for example, decisions about things such as supplier selection and inventory policy must take into account not only typical cost considerations associated with location, obsolescence, transportation, etc., but also must take into account the possibility that at some point a supplier may be unable to deliver the requested goods at the requested time which will affect the focal company's ability to achieved desired customer service levels.

These challenges led Melnyk et al.(2010) to argue that minimizing traditional cost considerations alone cannot be the only supply chain objective. The appropriate level of resilience and security to reduce disruptions in the supply chain to achieve desired service levels must also be taken into consideration.

A risk analysis approach that measures supply chain TCO then needs to be able to measure and predict the costs given the uncertainties of risk and contingency plans as they play out during the defined time horizon of the analysis. Further, as Fischhoff, Watson, and Hope (1984) argue, decisions about risk involve trade-offs among options and that other consequences must be taken into account. This line of logic implies, ultimately, that risk management decisions need to take into account not only the costs of risk in the current supply chain but also the risks and impact associated with whatever interventions may be made, such as contingency plans and mitigation strategies that may be put in place.

2.4 Supply Chain Disruption Risk Analysis and Management Approaches

Various methods and approaches have been studied and are used for diagnosis and resolution of problems in supply chains. These approaches have been developed to improve supply chain management in general and many offer at least some capabilities aimed at improving the management of risk in supply chains. A brief overview of various general approaches used for risk management in supply chains is presented here, providing some background for evaluating which general approach(es) is(are) most appropriate for the RSC*Model* tool.

2.4.1 Discrete-Event Simulation and Optimization

A study reviewing the applications of simulation in peer-reviewed literature spanning nine years from 1997 to 2006 by Jahangirian, Eldabi et al. (2010) indicates that simulation techniques in general are “the second most widely used technique in the field of operations management” and that discrete-event simulation (DES) in particular “is the most widely used technique in manufacturing and business.” Its use for modeling and analyzing entire supply chains is a more recent application, but the study also shows an increasing trend in simulation use for supply chain management “mainly because,” they state, “simulation is regarded as the main technique for supporting decision-making on supply chain design” largely because it offers flexibility in modeling. DES has been used for many years as a tool to analyze and make improvements at the factory level and has proven to be “appropriate for tactical and operational decision-making levels," being able to model and perform shorter-term analysis for "detailed processes, resource utilization, and queuing" (Jahangirian et al. 2010). Many of these capabilities have made it a good candidate for use as supply chain analysis tool as well.

Simulation allows the analysis to include random effects, dynamic behavior, simple modeling methods, analysis of time-dependent relations, and to capture uncertainty and complexity (Persson and Araldi 2009) all of which are important in risk analysis of complex supply chains with uncertainty in inputs that cannot be analyzed effectively through deterministic means. The authors explain further that simulation also offers capabilities "to experiment with a set of different scenarios in order to find an optimal solution." A main benefit of simulation based tools that makes them ideal for supply chain analysis is the ability to test proposed changes and strategies before "rolling them out in the real world," and allowing modeling and simulation of multiple scenarios for sensitivity and overall robust analysis for strategic planning ("About Us: The Llamasoft Vision" 2011). Simulation allows you to ask "what if?" and do "smart modeling" that stretches the model to see what would happen, and assesses the impact and how you would recover (Grackin 2011).

This relates to another analysis approach enabled by simulation. War gaming is a strategy development technique in which managers are faced with a conflict or challenge and are provided with a way to make and assess decisions, which is often achieved with the involvement of quantitative simulation software (Chussil 2007). War gaming is valuable because managers can "[test] action[s] in a realistic environment where mistakes don't count" and learn and improve the strategy before implementing it in real life. Although it typically involves competition among different persons or groups, simulation alone provides the basic elements needed to make and evaluate different decisions. In general, "simulation is very suitable for the analysis of complex and dynamic systems" making it an important and popular tools for supply chain design and planning (Dong et al. 2006).

While DES is a popular and widely used technique for improving supply chain management, it does have some shortcomings and difficulties. Jahangirian, Eldabi et al. note that there remains an important need to better understand the complexities of enterprises and how to appropriately use simulation to deal with the system as a whole. One problem these authors note is lower stakeholder involvement as compared to other techniques in part because of traditionally long lead times for model development and analysis. Persson and Araldi also point to several problems typically seen when using simulation for supply chain analysis including difficulty in choosing the correct level of detail for the model, incorporating the ability to handle different levels of detail within the model, and the difficulty, time, and resources required to create and validate models of complex systems where knowledge about the system is dispersed among multiple individuals. They additionally note that experimentation on typically large supply chain models often requires efficient experimental planning to deal with the vast number of possible alternate scenarios. They also argue that logistics processes have not typically been well supported in simulation approaches and tools. Logistics become more important when modeling and simulating supply chains rather than a single factory, for example.

An approach often discussed and used for similar problems is optimization. In their review of the literature, Persson and Araldi (2009) found that many supply chain models used currently and in the past have been used for static optimization of supply chains. Optimization can be valuable for strategic decision making in supply chains for inventory, supplier selection and location, transportation routes, etc. Optimization, however, has some important limitations. Many tools use optimization and it has been studied by many authors, but optimization techniques typically "consider the supply chain at specific instances in time and do not take on a dynamic view as is the case with simulation models" and "often lack an estimation of the variability or robustness of a solution in a stochastic environment" (Persson and Araldi 2009). Not taking into account the dynamic nature of the real supply chain, the necessary use of static models for optimization results in solutions for only a specific supply chain scenario. This limits the usefulness of optimization in meeting the needs for managing risk in today's supply chains, although it can still add value in identifying preliminary optimal strategies.

2.4.2 Benchmarking

Benchmarking is a common diagnostic approach used to help identify problems in a supply chain through comparison of quantitative measures of performance among different, often competing, companies in order to evaluate performance and identify best practices (Foggin, Signori, and Monroe 2007). Companies can use benchmarking techniques to identify symptoms of potential problems in their supply chains by comparing metrics of their performance against those of other companies in their industry and identifying those metrics that may indicate where the company may be at risk. Foggin, Signori, and Monroe also explain how comparing combinations of metrics can help identify root causes of problems in the supply chain. Benchmarking techniques could be useful for disruption risk management by helping to identify symptoms that may ultimately result in a disruption in the supply chain. Benchmarking metrics related to suppliers, for example, may help identify which suppliers may be at risk of causing a disruption because of failure or production or transportation issues. While potentially helpful and widely used, benchmarking has some drawbacks as described by these same authors. The primary problem is that gathering and maintaining accurate, compatible, and up-to-date data on metrics in a benchmarking database for various related companies can be time and resource intensive, although some commercially databases are available that may be suitable for some industries where there are similar companies with similar supply chain strategies and readily available information. Another identified drawback is that benchmarking primarily helps with identifying symptoms of problems and does not automatically provide information on why problems, such as disruptions, may occur.

2.4.3 Mapping

Another typical approach described by Foggin, Signori, and Monroe that has been used as part of risk management efforts is that of “mapping.” The primary goal of mapping techniques is to help identify root causes for problems, such as supply disruptions, in a supply chain. The approach helps improve visibility in the supply chain by creating a representation of the supply chain’s complex relationships among processes and firms and the product and information flows in the network which is a key element in better understanding and therefore managing supply chains. Some mapping tools such as SCIM*am* are designed to help evaluate “the organization’s ability to manage the supply chain in different scenarios.” SCIM*am* uses radar charts to compare what will happen in different scenarios in an “as-is/what-if” type approach based on different key performance indicators.

While mapping type approaches can help identify sources of risk and potential consequences they have a few limitations. The main drawback is that mapping type approaches alone don’t allow the user to dynamically assess or predict the supply chain behavior under various conditions and to quantify consequences in a robust manner for unique systems thus limiting their ability to validate proposed strategies or “to-be” process maps.

2.4.4 Cause-and-Effect Diagrams

Cause-and-Effect and Means-Ends type approaches also exist that aim to use a structured approach to link risk sources to potential consequences. Fault tree analysis (FTA) and event tree analysis (ETA) are logic diagram approaches that aim to identify "factors and causes" and to map how they propagate through complex systems such as supply chains to contribute to "accidental events," such as supply disruptions (Norrman and Jansson 2004). FTA and ETA present graphical logic diagrams of how a systems can fail (i.e. what are the events leading up to the failure) and what failures and consequences could occur because of various events, respectively. As mentioned previously, Failure Mode and Effect Analysis (FMEA) is a similar tool used in quality management to help identify root causes of risks and trace them to potential consequences. Two other tools mentioned by Foggin, Signori, and Monroe (2007) are Quick Scan and Diagnostic Tool, each offering a unique method to link symptoms with root causes. These tools could be helpful to identifying potential disruption risks and to link them to their root causes and even link them to possible consequences. As such, the tools could help understand where and why risks might occur and where action could be taken to reduce or eliminate root causes, but they don't help quantitatively identify and assess the full impact of risk events or results of new management strategies.

2.4.5 Bayesian Networks

Bayes' theorem is a simple mathematical formula used for calculating conditional and inverse probabilities ("Bayes' Theorem" 2011; Joyce 2003). The simple version of Bayes' theorem can be represented as seen in Equation (2-5). Bayes' theorem allows you to calculate the conditional probability of 'A' given 'B' by knowing the probability (likelihood) of 'B' given 'A' and the marginal, or unconditional, probabilities of ‘A’ and ‘B’. So, for example you can calculate the probability of a delivery being late given that it is shipped via rail, P(A|B), by knowing the probability that the delivery is via rail given that it is late P(B|A), the probability that a delivery is late P(A), and the probability that the delivery is via rail P(B), where event A is that the delivery is late and event B is that the delivery is via rail.

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{2-5}$$

Bayes’ theorem is used as a risk management approach in tools that use the basic concept to create Bayesian Networks that act as causal models or risk maps to link various events, triggers, controls, mitigants, and consequences of risks in a supply chain as described earlier, and to calculate and propagate probability values forward and/or backward through the causal chain. Fenton and Neil (2006a; 2006b) argue for the need and value of the Bayesian network based approach such as that used by AgenaRisk and related tools. They argue that while the traditional view of risk as a probability times impact could provide a value useful for prioritizing risks, it is in most cases irrational and the value meaningless since you typically cannot get the numbers needed to calculate a risk value since they involve conditional probabilities and impacts that are affected by various other triggers, controls, and mitigating events and activities. Instead they argue risk maps and Bayesian algorithms allow the use of more easily obtainable or accurately estimated unconditional probabilities for root cause triggers, controls, and mitigants to arrive at reasonable estimates for conditional probabilities for risk events and defined consequences. A benefit is that Bayesian networks can use either historical data or expert opinion to make probability predictions and sensitivity analysis can be performed to estimate probability values based on assumptions that risk events do in fact occur.

2.5 Review of Supply Chain Risk Management Tools and Methods

A review of several specific tools for supply chain risk management (SCRM) is provided here. A few tools with the greatest significance for this thesis, including some other tools being developed under government funded contracts, are reviewed in greater depth. These tools are reviewed for overall functionality, and in the case of the government funded tools, for integration potential with RSC*Model*. As an outcome of these reviews, the integration potential is explored more in Chapter 4. Where possible the expected ease of use for the tools is also examined. The review of the remaining tools is, by necessity, more brief and is concerned primarily with the identification of the potential capabilities and use of the tools as it relates to the management of supply disruption risk in supply chains. Although various techniques have been and are used for risk management, based on the discussion in the previous section (2.4), a special focus is given in this thesis on tools using simulation based techniques.

2.5.1 PrimeMap and PrimeSupplier

As part of government-funded efforts to develop more effective supply chain analytical tools, NASA has developed two "next generation supply chain applications" called PrimeMap and PrimeSupplier which are both aimed at supplier risk identification. These products were assessed in detail as part of the project requirements for RSC*Model* to assess and identify how the capabilities of other government-funded supply chain analytical tools could be leveraged and what synergies and integration possibilities might exist for using the tools in combination with RSC*Model*. Basic details of the functionality, capabilities and use of PrimeMap and PrimeSupplier were found through various internet sources and a conference call held in April 2011 with a supply chain manager at NASA and project lead for both products.

PrimeMap and PrimeSupplier were developed in response to the need to manage the NASA supply base during space shuttle transition activities (Chowske 2009; "Counting the Links in the Supply Chain: What Impact Will Shuttle Retirement Have on the Human Spaceflight's Supplier Base?" 2009; Galluzzi 2009a; Galluzzi 2009b; Galluzzi 2009c; "John F. Kennedy Space Center's Primesupplier Software" 2009). PrimeMap is a web-accessible supply chain and disaster visualization and assessment tool using commercial mapping software and a custom user interface developed by Advanced Core Concepts. PrimeMap uses real-time data feeds from sources such as the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS) for current and historic disaster information. It provides various filtered, geographic and “org. chart” style views of the supply base based on disaster affected areas, congressional districts, supplier demographics, programmatic information, etc. PrimeMap also provides access to supplier specific information on performance, capabilities, ratings, and other measures fed from other sources. With these capabilities, PrimeMap’s main strength for use in supply disruption risk management is that it provides a visual way to identify and assess the potential impacts of supply disruption risks on the supply chain from actual current and historic natural disaster data. It appears, however, that the time and effort currently required to gather and maintain all necessary supplier information to make effective use of PrimeMap’s capabilities can be prohibitive. Access to and availability of information is key and “seamless CAD/CAM interface to … enterprise data management tools” (Galluzzi 2011) (such as SAP, etc.) is vital to ease this burden.

PrimeSupplier is a supplier “stability index” model that produces a quantified Total Risk Factor for each supplier based on risk factors associated with economics, supply chain operation and supply chain readiness. Individual risk factors in each of these areas are measured on a scale from zero to ten through comparison to industry benchmarks. An aggregate risk rating for overall financial, operational, and supply chain risk is provided as calculated from individual risk factor weightings and risk values. The sum of category risk values gives the Total Risk Factor for each supplier, which is a weighted average of all individual risk factors values. One of the major strengths of PrimeSupplier compared to many other supply chain analytical tools is that it takes into account not only financial risks but also programmatic, demand, and supply chain data, where most other tools look only at financial risks. A challenge with PrimeSupplier, as with many such applications, is that suppliers may be reluctant to provide necessary information to support full program functionality. PrimeSupplier is currently an "internal" NASA application that appears to use Microsoft Excel for the primary user interface which creates flexibility in potential future applications of the tool. A link to Dow Jones' *Supplier & Risk Monitor* is planned for future implementation for access to risk related supplier data.

Both PrimeMap and PrimeSupplier have applicability beyond the aerospace and defense industries but currently remain very NASA centric in their functionality and their focus on projecting risk in government supply chains which limits widespread commercial use of the products for supply chain risk management. Future developments aim to link the two applications and feed PrimeSupplier risk data to the supplier performance information presented within PrimeMap, with the mapping function from PrimeMap being the primary visual anchor. Both tools hold promise for commercial application beyond aerospace and defense but remain very NASA centric and need some further technical development. Neither product currently supports simulation although future development efforts aim for integration of Monte Carlo and Discrete-event simulation methods which could help provide for optimized programmatic and configuration decisions and add a dynamic aspect to risk identification and assessment. As they now stand, the tools remain focused on supplier risk identification and not on the evaluation of the resultant impact of risks and the effectiveness of risk management strategies.

A list of survey questions and full product summary and integration report was prepared as part of the PrimeMap and PrimeSupplier assessments and can be found in Appendix D.1 and D.2 respectively. A diagram of PrimeMap and PrimeSupplier inputs and outputs was also prepared, as well as a diagram of the proposed link between the two products, and can be found in Appendix F.3, F.4, and F.5 respectively.

2.5.2 Risk Assessment for Next Generation Supply Chain Readiness (RANGER)

RANGER (Risk Assessment for Next Generation Supply Chain Readiness) is a Department of Defense (DoD), adaptable risk assessment and identification tool (Burnette 2010). RANGER, like the NASA Prime products, was assessed in detail as part of the project requirements for RSC*Model*. Basic details on the functionality, capabilities and use of RANGER was found through internet sources and a conference call held in April 2011 with the program manager.

RANGER uses commercially available AgenaRisk software to aggregate risk probabilities for one or more of 10 possible performance “drivers” based on Bayesian Network algorithms and selected risk elements from a dynamic, research based risk taxonomy of 155 risk elements (such as likelihood of disaster, etc.). As such, it can quantitatively *describe* the effect of user selected risk probabilities on a performance driver. Conversely, it can also be used to quantitatively *prescribe* risk probabilities to achieve a target resultant risk probability for a selected performance driver. With this ability to evaluate and calculate risk probabilities, RANGER provides a methodology for evaluating risk avoidance and mitigation strategies by analyzing their effect on the performance driver of interest and pinpointing the greatest risk factors in a supply chain. RANGER also has the benefit that models can be created at different levels of detail which makes it adaptable to a wide range of applications, from small work cells to global supply chains.

A proof of concept model for RANGER has been completed and the product is now in a Beta testing phase and has yet to see any widespread commercial use. Gathering and inputting data to describe supply chain risks is largely a manual process and requires significant upfront effort and expertise although future developments are aimed at improving the user interface to make the product easier to use. Access to supply chain and probability analysis data for integration or use with other supply chain analytical tools was found to likely be feasible through the import/export features of the AgenaRisk software. In sum, RANGER provides an effective method for accurately identifying supplier failure risk probabilities at each node in a supply chain and for quantifying the propagation of these probabilities both forward and backward in the supply chain. The risk analysis performed by RANGER, however, is a static analysis providing only the probability of an event. It does not account for the timing of events, and state changes over time that may be caused by the event.

A list of survey questions and full product summary and integration report was prepared as part of the RANGER assessment and can be found in Appendix C.1 and C.2 respectively. A diagram of RANGER inputs and outputs was also prepared and can be found in Appendix F.2.

2.5.3 Supply Chain Guru

Besides the government funded tools reviewed, one of the most important tools identified for this study is Supply Chain Guru (SCG) created by LLamasoft Technology. SCG is the company’s flagship product touted as an industry *leading* software application for supply chain network design for “enterprise strategic planning and targeted supply chain performance improvements" using both optimization and simulation in a single modeling platform to provide users with the capability to "model, analyze, optimize, and simulate their supply chain network operations" ("Supply Chain Guru: Supply Chain Design Software" 2011). The main value proposition of SCG is as a supply chain design and predictive analytic tool that "enables companies to model their [end-to-end] supply chain operations, optimize their structure [and operations] for cost and profitability, and simulate results," allowing companies to reduce costs and increase profits while maintaining or improving service levels and mitigating risk (*Rapid, Effective Supply Chain Network Design* 2011).

SCG is an example of a modern tool applying discrete-event simulation at a higher level than more traditional applications for analysis of facilities and logistics processes. SCG provides capabilities for more enterprise level modeling and simulation of supply chain networks. Using a proprietary simulation engine, SCG can model and analyze "millions" of locations and SKUs individually or as groups, making SCG very flexible in terms of the level of detail at which supply chains can be modeled and analyzed. Complex supply chains with details such as business rules and constraints, site capacities, transportation assets, and facility processes, work centers, and resources can be modeled allowing the user to understand the interdependencies and impact each variable has on supply chain performance and financials. The high level of detail possible also permits the user to better analyze, understand, and optimize the various trade-offs among cost, service, time, and capacity based on the variables of the supply chain network structure and policies to achieve strategic objectives.

SCG provides optimization techniques and routines and multi-scenario simulation analysis that allows for the identification of "optimal" management strategies for network design and operating policies (configuration and coordination), product and customer selection (cost-to-serve analysis), inventory, production, transportation, and strategic sourcing. The optimization techniques used appear to be primarily traditional optimizations techniques that lack dynamic analysis and involve multiple simplifying assumptions with a focus on the network structure but ignoring the more complex and variable behavior of the system. These constraints limit the ability of SCG to provide a perfect answer for all situations through optimization techniques alone. Simulation capabilities in SCG then become valuable to supplement the optimization capabilities, and provide "feasibility" testing and further solution refinement through multiple-scenario, "data-rich" analysis with stochastic conditions that more closely resemble reality. To further enhance the usefulness of simulation SCG provides a seemingly novel way of simulating various scenarios by simply allowing the user to enter a range of values for data input fields and then automatically running simulations for those ranges, although it is not entirely clear how this works and if this is simply the ability to include probability distributions for input ranges as in many other simulation tools. Similarly, optimization routines can have bounds or constraints defined for input variables that limit the range of possible values.

SCG provides speed and ease of model building through various time and resource saving capabilities. When defining the supply chain in a model various pre-defined business policies can simply be chosen for inventory, sourcing, transportation, and production processes. SCG can also import needed input data from external databases. The tool has "certified data connectors" that make it capable of automatically extracting data and information from major ERP and other systems and programs, including Microsoft Office applications, that is required for modeling a supply chain (*Cost-to-Serve Optimization* 2010; *Rapid, Effective Supply Chain Network Design* 2011) such as site locations, demand projections and network operating rules and policies ("Risk Analysis / Contingency Planning" 2007). With these data links SCG is promoted as providing the ability to nearly automate the creation of a baseline supply chain model. The majority of the supply chain network locations and relationships can be formed by importing a “shipment file” and then “drawing the network” on a virtual “canvas.” Other data, such as transportation cost information from rate tables, can also be imported. Such capabilities to import and use data can significantly reduce the time and resource commitment needed to gather, manipulate, and enter data to build and simulate models. Entry of additional data, policy definitions, and other inputs are done visually through a graphical user interface. Existing supply chain network models can, according to promotional literature, also be easily modified through “drag and drop” type action in a graphical user interface. The visualization capabilities of SCG allow the user to view the supply chain network in Google Earth and to individually view product chains by filtering out the rest of the chain, providing a familiar and powerful way to visualize the network design.

To further improve ease of model creation, especially for large complex models, business processes and policies in the model can be created and modified individually or in batches. This includes the ability to create group rules and policies for customers, products, sites, transportation modes, etc., and to aggregate and disaggregate demand where appropriate for the type of analysis, which allows for the use of a single global, SKU level demand file that can be used for every type of analysis. If more advanced model features are required, a scripting language is also available to fully customize any model, although, as with any tool offering advanced programming this would increase the level of experience required.

Once models are created, SCG provides methods to detect for “infeasibility,” or problems with a supply chain model before attempting to optimize or simulate which can help improve the efficiency of model creation and analysis especially with large supply chain models with lots of data and references between objects. Knowing when and where there is a problem in a large complex model can be an important time saver. These capabilities can make it much easier for users with little or no prior modeling or simulation experience to use the tool to improve managerial decision making.

Following modeling, and optimization and simulation runs, SCG provides multiple standard output reports and filtered views of data and graphical reports and allows for comparison of output data from different models in a side-by-side view. Additionally, any output data can be exported to Excel or can be linked to an external, web-based analytics tool to enhance further statistical and graphical analysis of the outputs. It is unclear which standard data sets and reports are generated by the tool.

An additional feature of the SCG software that increases its potential to be an efficient supply chain management tool within organizations is the availability of a web-based version of the tool. This can greatly improve the sharing of information, models, and analysis results among various decision makers in a company, making it easier to understand and more quickly assess supply chain status and formulate management strategies as a group.

These various capabilities of SCG appear to have potential in improving management of disruption risk in supply chains. It is unclear, however, which capabilities provided in SCG allow the incorporation of risk as part of the model and scenarios to be analyzed and/or optimized. It is stated in promotional literature that SCG permits the “[analysis] of risk by evaluating alternate scenarios” (*Cost-to-Serve Optimization* 2010) and that "analysts can introduce disruptive events or supplier uncertainty into the network to get a better understanding of the robustness of their supply chain" with "detailed reporting for in-depth supply chain risk analysis" ("Risk Analysis & Contingency Planning" 2011) to transform a supply chain from an accident waiting to happen to an "intentionally engineered, robust and resilient network" (Gallagher 2011). Statements made about the ability to model supplier uncertainty as a form of risk implies that SCG may also be able to model supplier disruption with some sort of probability of a risk event occurring, such as a supplier possibly not remaining economically viable. It is unclear however, if this “supplier uncertainty” is referring to costs, ability to produce, or some other supplier variable.

These statements imply that, at a minimum, a user can include some type of disruptive event into any user defined network and scenario and run simulations and generate output data for analysis of corresponding supply chain performance, including costs and service levels achieved. These results could be compared against those of other possible scenarios. This would include the capability to performance sensitivity analysis on the model for varying degrees of risk, which would allow the user to test the resilience of the supply chain and make sure it does not perform unacceptably poorly (*Assuring Maximum Effectivity in Supply Chain Strategic Planning* 2008).

Additionally, it is either stated or implied that with SCG you can include in the model and scenarios various “alternate” supply chain network options, such as alternate supply sources, transportation modes and routes, and conditional production processes and production facility and distribution center capacities “that may be required to meet desired service levels” following a risk event. Changing costs for such alternate network options can also be assigned and tracked. The implication here is that some form of contingency plans could be included in the model where some event or condition triggers the use of alternate suppliers, transportation modes, etc., and the resulting performance can be tracked along various measures. As a robust modeling and simulation tool, it would allow the user to weigh the severity of "perceived risk factor(s) versus the costs of implementing a contingency plan" (*Assuring Maximum Effectivity in Supply Chain*

Strategic Planning 2008) by testing the resiliency of the supply chain and the operational and financial effectiveness of contingency plans. This also implies that more proactive changes to the network and policies could be modeled and tested in anticipation of disruption risks to create a more resilient and lower cost supply chain design. In general, these capabilities indicate that SCG could provide a valuable method for formulating, testing, and validating possible risk mitigation techniques and be an effective tool for the risk treatment and handling phase of the basic risk management process described earlier in this chapter.

A major drawback of SCG is that it appears to have no systematic method of determining what risks of supply disruption exist in the supply chain. Despite the power of the data links possible in SCG, they appear to only be for information regarding the network relationships, demand, inventory, bill of materials and similar data. No reference was found in available literature about the ability or predefined methods for the software to connect to and extract data related to the identification in either quantitative or qualitative terms of supply disruption risks in the supply chain. This implies that any capability to model, analyze, and formulate management strategies for supply disruption risks would likely involve some form of manual gathering and/or entry of risk data. Indeed it is stated that SCG "relies heavily on the knowledge and expertise of its users with regards to both existing operations as well as potential risks" for use as tool to aid in risk management (*Assuring Maximum Effectivity in Supply Chain Strategic Planning* 2008).

It can, however, be inferred from descriptions of other capabilities that SCG could be used to provide at least some useful information for identification of potential disruption risks. Many of the same tools provided in SCG for supply chain network design, such as decisions on where to locate distribution centers and manufacturing capacity to most cost effectively respond to customer demand with the lowest inventory and transportation costs, could also be used to identify, analyze, and make strategic decisions about risk in the supply chain. One example is that SCG allows the user to view the supply chain network in Google-Earth which means that the user could visually observe the network in relation to real-time weather information, providing a potentially simple means of identifying risks of disruption in the transportation of goods in the supply chain. The ability to model in low-level details, such as including transportation assets, and enhanced logistics modeling features in SCG can also help the user identify and understand low-level sources of supply disruption risk. For example, by simulating various potential supply chain scenarios the user could potentially anticipate a disruption in transportation or production of goods because there is a shortage of shipping containers or other bottleneck. Essentially anything that could lead to a stock out in any part of the supply chain is a type of disruption and SCG, therefore, could also help to predict any disruption risk by allowing one to simulate the supply chain to predict service rates, inventory levels, and capacity constraints. Sensitivity and "what-if" analyses through multi-scenario simulations could be used to identify where such disruptions may occur, which disruptions have the biggest negative impact on performance, and to what extremes variables must be taken for those disruptions to occur.

Risk analysis is also related to the overall analysis of the end-to-end supply chain which, in SCG, involved inventory and cost-to-serve optimization, strategic sourcing, transportation and production modeling, and network design. An option in many risk mitigation efforts is the use of alternate sources of supply and/or transportation, which involves the process of making decisions on sourcing and transportation assets, modes, routes and carriers. Inventory strategy, including the quantity and placement of inventory, is another important option in mitigating risk as are the decisions on where to locate suppliers and distribution centers. SCG provides various modeling and optimization techniques for these options that could potentially offer significant guidance on the lowest-cost method to deal with disruption risk *if* those risks could be included in the analysis, which is not clear. Through inventory and capacity modeling and simulation SCG could help optimize for the lowest-cost plans to manage inventory and operations that also satisfactorily provides desired service levels in order to deal with disruption risks. This includes robust calculations of cost associated with inventory such as activity, handling and stock costs. SCG also provides capabilities to analyze and optimize inventory with seasonality of demand which could improve both identification of disruption risks from capacity type constraints as well as provide for a more robust testing of mitigation strategies under more realistic test cases. Transportation modeling allows the user to model and simulate alternate transportation options, optimize transportation plans, including optimizing transportation asset levels, given defined cost and service constraints, which could aid in mitigation strategy formulation. Cost-to-Serve Optimization capabilities are also provided which allow for a financial analysis of the entire supply chain to determine how to achieve "required customer service levels" at the lowest true total cost required to fulfill end customer demand which involves choosing which customers to serve or not to serve. Some disruption risk events may require a choice as to which customer to serve and such cost-to-serve capabilities could prove valuable. It is implied in the literature that finding the total cost to serve for these decisions in some way can include the costs associated with risks in the supply chain. Supply Chain Network Design optimization capabilities can help identify the most cost effective network design decisions which could also be valuable if combined with risk modeling.

These capabilities can help the user understand the various trade-offs involved in supply chain decisions such as those between cost and time, cost and service, service and capacity, fixed and variable cost, etc. In general, with all these capabilities SCG could be useful for risk management because it can not only help analyze the current network and the various trade-offs involved in decisions, but also through simulation it can predict the performance and costs for a proposed network and set of policies such that new strategies for risk mitigation can be tested. A major part of this is the robust features that SCG has for allocating and tracking costs in the supply chain.

2.5.4 Typical Proprietary Simulation Tool

Another tool attempting to use discrete-event simulation to improve the management of supply chain network disruption risk in a supply chain is that developed by a leading U.S. aerospace and defense firm for analysis of risk in a new 'space vehicle' supply chain. This tool and its development effort and use are described in a thesis by Wilson (2010) and was also worked on personally by the author of this thesis. It is included here primarily as an example of a typical simulation tool that a company might develop to analyze their supply chain. Like RSC*Model* the tool is built on standard discrete-event simulation software using Excel as the primary user interface for both data input and for reporting of simulation results. The modeling of the specific supply chain network and operating policies, however, are created primarily through "hard coded" methods directly in the simulation software. For analysts and decision makers not familiar with the modeling software, the use of Excel improves ease of use for data entry and understanding and manipulating reported output data. The modeling approach used also demonstrates the flexibility possible in such discrete-event simulation models. This tool shows how the modeling of various suppliers in the supply chain could be done at different levels for each supplier. Wherever possible the major internal production processes of the suppliers are included in the model to improve the level of resolution to evaluate and pinpoint problems. For those suppliers whose information on production processes are either unknown or detailed information cannot be easily obtained, however, the supplier is simply represented as a node in the supply chain with a total process duration as the input for the total expected time for the supplier to produce its subcomponent(s).

The tool is intended to both help determine the effects of disruption risks on the specific supply chain in question and to help identify and predict potential sources of disruptions. The tool was developed initially to only model the critical path of the supply chain although with more time and resources it could be expanded to include other branches of the supply chain. The initial model includes the subcomponents and production processes and routing rules, including quality tests and rework routes and durations, of a major subcontractor and several upstream suppliers through the final assembly operations of the complete space vehicle by the aerospace company and final delivery to the end customer. The tool was designed with three primary purposes in mind: analyze the effect of process variation or “randomness,” quality failures, and the impact of production disruptions on supply chain performance. The primary focus of the tool is on determining the effect of these conditions on the “total production duration time” of the supply chain for completion and delivery of a single space vehicle.

Once the supply network, components, relationships, routings and behavior are defined the model inputs include mean process times, quality test passing rates, rework times and disruption durations. These can be easily input and changed via the Excel interface by a user with no modeling experience to run various scenarios. Disruption durations can be entered either as deterministic times or as a probability distribution to allow the time to be selected randomly from the distribution for each simulation replication. A unique feature of the tool is that a “stochasticity factor” can be applied to specific groups of processes or the entire model to define a “randomness” factor based on the defined production mean times. While limitations exist with this universal "stochasticity factor" approach, it does provide a way to add variation throughout the model when only a general assumption on the amount of variation in the system can be determined. It also helps to reduce the burden of data collection while still allowing the supply chain to be more realistically modeled with variation in processes which can alter the analysis of risk and formulation of risk mitigation strategies.

With these inputs the tool allows for the simulation of various disruption scenarios and for the user to see what disruptions may occur given variation in production and defined quality test passing rates. Scenarios ranging from suppliers not providing parts on time to quality test failures, to disease pandemics can all be considered. For defined disruptions, the actual source or reason for the disruption is not particularly important as only data for the location and duration of the disruption is needed for the simulation.

Simulations can be run with multiple replications to capture the effects of randomness in the system which is shown in output reports indicating percentile rankings of total supply chain production duration times. The percentile outputs from different scenario simulations are used as confidence intervals that let the user understand what the probability is that the supply chain will achieve its schedule or that there might be a problem. It also allows the user to perform sensitivity analysis and test the effects of different disruption and production scenarios to help identify where the greatest vulnerabilities might exist. The tool can be used with expected values to analyze the supply chain during the design phase to improve the resilience of the supply chain through improved design and it can also be used with up-to-date information or revised estimates to help analyze the current status and predict where disruptions may occur that have an unacceptably high probability of negatively affecting the production schedule. The model was shown in the Wilson thesis to be potentially useful throughout the life cycle of the product in question as a tool to evaluate production buffers and the ability to meet target production dates given current data on production and disruptions. The simulation tool was being used by the aerospace company during the supply chain design and production ramp up phases to help identify areas where the supply chain may be either very vulnerable or susceptible to disruptions so that such issues could be identified and mitigated before they actually occurred in the system.

Mitigation strategies such as "smart sparing" described by Wilson can be analyzed with the tool to assess the potential to mitigate the impact on the production schedule of disruptions. Testing these types of scenarios, however, often involves changes to the supply chain structure or operating rules. These types of changes are more difficult and usually require the involvement of someone with modeling experience and familiarity with the hard coded workings of the model. Because of these limitations, the tool doesn't easily allow much for conditional mitigating efforts to be simulated and analyzed such as switching suppliers when a disruption occurs or changing inventory policies. Some of these scenarios can be represented in the tool in a more obscure manner by including, for example, the possibility of bringing on a new supplier into a conditional value for the duration of disruptions by lowering the disruption time to include only the time to bring on the replacement supplier. These approaches, however, can make it more difficult to arrive at reasonable values for the expected durations of disruptions.

These limitations demonstrate a shortcoming of this approach and that of many other similar simulation based tools built using traditional techniques with popular discrete-event simulation software platforms. While the modeling approach using hard coded logic can be used to create powerful and complex simulation models, it does not provide a universal tool for risk management that is simple to adapt to various analysis situations. The use and creation of models with hard coded logic for the supply network and behavior is common for many such projects, however, being built for a specific supply chain network limits the usefulness of the tool beyond the supply chain in question and, as discussed, can even limit its usefulness as a risk management tool for the represented supply chain. Specific supply chain models are typically harder and more time consuming to modify and require an experienced modeler to make any modifications. This limits the ability and ease with which various decision makers can experiment with different network configurations and policies in testing and formulating risk management strategies. Also, any options for formulation of mitigation strategies and tracking of key variables, such as costs, which is missing in this tool, must be specifically created for the model, further increasing the time and effort required to create and use such an approach and typically does not provide much if any versatility for analyzing other supply chains.

Further, the experience on this project also pointed out a major challenge likely faced on any supply chain simulation project. For any model of a supply chain to be useful it requires accurate and up to date information related to the various suppliers in the supply chain. If the author's personal experience working on this tool shows anything, it is that gathering and maintaining that data can at times prove very challenging especially when suppliers do not readily agree to provide the needed information in a timely and open manner and when electronic means of data gathering do not exist either due to technical limitations or lack of supplier consent. There are many reasons why obtaining needed information from suppliers is often difficult; however, this is not the focus of this thesis.

2.5.5 The Supply Chain Operations Reference (SCOR) Model

The supply chain council, a non-profit organization aimed at helping participating member corporations "make dramatic and rapid improvement in supply chain processes" ("Supply Chain Council - Membership" 2011), has developed and maintains the Supply Chain

Operations Reference (SCOR) model. The SCOR model is a cross-industry standard diagnostic tool that "provides a unique framework that links business processes, metrics, best practices and technology features into a unified structure to support communication among supply chain partners and to improve the effectiveness of supply chain management and related supply chain improvement activities" ("What Is Scor?" 2011).

Foggin, Signori, and Monroe (2007) classify SCOR as primarily a benchmarking tool although its usefulness seems to extend beyond those offered by typical benchmarking techniques alone. Dong et al. (2006) indicate its usefulness for process reengineering and measurement as well. SCOR is used to describe, measure, and evaluate nearly any supply chain configuration for continuous improvement of performance and enhanced strategic planning. These task are made possible through three major components (Persson and Araldi 2009) that provide (1) a set of standardized supply chain processes used as building blocks to map new or existing supply chains, (2) a set of key performance indicator (KPI) metrics to measure supply chain performance, and (3) capabilities to benchmark KPIs to other firms in the industry to analyze performance. Persson and Araldi further explain that the standardized set of processes is defined in three levels with the top level processes consisting of plan, source, make, deliver, and return. Performance attributes in two categories, customer facing performance attributes (including reliability, responsiveness, and flexibility) and internal-facing performance attributes (costs and assets) are also tracked with a set of metrics attached to each.

Kleindorfer and Saad (2005) indicate that central aspects of the SCOR model and approach can aid in improving the cooperation, coordination, and collaborative sharing of information and best practices internally and among supply chain partners that is necessary for effective disruption risk management. The standardized terminology, processes, modeling, approach and metrics in SCOR can improve the capture of the “as-is” supply chain and help develop an effective “to-be” future state with a unified supply chain strategy and performance tracking method, which ultimately acts to reduce the risk of disruptions. SCOR can also help identify possible risks as a visual mapping tool of the supply chain. Risk metrics for “value at risk” and “risk mitigation costs” for each top level process as well as various risk management processes themselves and risk management best practices are now included in the most recent versions of the model (*Scor: Supply Chain Operations Reference Model - Version 10.0* 2010). This can help make sure that business processes in the supply chain follow best practices for supply chain management and that important metrics are identified and tracked for risk monitoring.

2.5.6 Other SCRM Tools and Methods

Some tools developed for supply chain analysis attempt to combine different management approaches. The approach of several tools is to combine the SCOR model with simulation techniques. Persson and Araldi (Persson 2011; Persson and Araldi 2009) report on an effort to create a "dynamic supply chain analysis tool" that integrates the SCOR model with discrete-event simulation techniques. These authors have and continue to develop an integration of the static SCOR model with Arena discrete-event simulation software to create a reusable modeling framework for analysis of supply chains. The authors created a template of the SCOR model in Arena "to create an easy-to-use, graphical interface for simulation modeling of supply chains."

Using simulation building block modules in the template based on standard SCOR processes, the user can model the supply chain in a drag and drop fashion by creating nodes of source, make, and deliver processes for each supplier in the network. Various policies and parameters, such as production and inventory replenishment policies, are defined by the user for each product type in a similarly simple manner. Data for customer orders in the model can be imported from Excel or can be based on stochastic values. The entities in the simulated system track various attributes making it possible to gather data on nearly all SCOR metrics. Industrial test cases with the SCOR simulation approach showed it to be a "useful tool for visualizing a supply chain configuration … and to test 'what if' scenarios in a dynamic simulation setting."

Similar tools attempting to combine SCOR and simulation exist such as Gensym's e-SCOR (Albores et al. 2006; Persson and Araldi 2009) and IBM's SmartSCOR (Dong et al. 2006). IBM SmartSCOR is described as "a comprehensive framework and methodology for On-Demand SCM problem-solving based on the cross-industry process standard SCOR model and a variety of simulation/optimization techniques." The focus of SmartSCOR is to leverage the strengths of both SCOR and simulation to enable effective "supply chain transformation" by improving the ability to fundamentally change the supply chain for strategy design/redesign and for supply chain process improvement by aligning and streamlining business processes to match the strategy, ultimately "maximizing performance … while reducing costs."

Tools such as these that combine the SCOR model with simulation provide several possible benefits. In analyzing and comparing SCOR based modeling techniques, such as e-SCOR, to traditional general purpose simulation tools Albores et al. (2006) found that by using the standardized processes and metrics provided by SCOR these simulation tools benefit from easier communication which leads to faster model building and better understanding of results (Albores et al. 2006). Albores et al. also point out that the pre-defined library of terminology and objects based on the widely used, understood, and accepted standard SCOR process definitions allows for quicker and easier model building because the logic for the processes is already built into the objects. The SCOR model is popular, and adapting it to support simulation provides a familiar method, terminology, and metrics making it easier to model, simulate, and analyze the supply chain. Persson (2011) reports that with the latest version of the SCOR simulation template a "reasonable sized" supply chain model with about three nodes can be model in less than an hour. Persson and Araldi also note that model validation is also simplified because it is based on the pre-validated, universal process steps of the SCOR model, although Albores et al. argue the complexity of SCOR can easily lead to creation of invalid models.

In developing their tool Persson and Araldi also found that the predefined process levels in SCOR help eliminate the challenge in most supply chain models with the appropriate level of detail. Albores et al. found that e-SCOR type tools provide a way to quickly create models at supply chain network level of scope, but also allow for selective areas of the network to be modeled in greater detail. This allows the user to see the effects on the whole system from changes made in those more detailed areas. Albores et al. also found an advantage in that SCOR based approaches can easily model information flows and typical business process events such as supplier selection, logistics mode selection, etc. that more traditional generic simulation approaches do not readily make available.

These authors did find some drawbacks as well. Albores et al. found that general purpose simulation tools have greater flexibility in "representing the target system … and the actual nature of the business processes" and can therefore create a more valid model that better represents the real system in more situations. SCOR based models at times require users to represent the system with standard processes that don't reflect the actual nature of the real business processes, although this can be overcome if the underlying simulation tool provides custom logic building capabilities. They also found that general purpose simulation tools can also present more accurate visual representations of dynamic supply chains than with the SCOR approach which represents the system in a flow chart type presentation. Additionally, they found that SCOR based systems are typically constrained to report pre-defined metrics which may be limiting where more custom metrics are desired. An additional major shortcoming is related to one of its strengths in that SCOR focuses on the higher level supply chain operations, and not so much on the lower level operations of system such as the production processes (Persson and Araldi 2009). This makes it well suited and easier for modeling and analyzing at the supply chain level, and good for formulating supply chain level strategies. At the same time, however, this also limits the user's ability to understand exactly how a model will behave and what the resulting performance of the supply chain will be for a new strategy developed with the tool.

Curiously, there seems to be little to no mention in literature of SCOR based simulation tools directly addressing risk in supply chains, perhaps because the inclusion of risk management in the SCOR model is still a relatively recent addition. It is unclear how widely any SCOR based simulation tools have been used beyond academia and selected pilot research projects.

IBM General Business Simulation Environment (GBSE) is a discrete-event based supply chain simulation tool designed to model and simulate supply chains at a low level with many details including processes for order handling, inventory control, manufacturing, transportation, procurement, and planning, so that insights can be gained about the supply chain's real operations (Wang et al. 2008). The tool is designed to be a generic simulation tool suitable for a variety of business purposes. Like typical discrete-event simulation tools it supports stochastic modeling and is described by Wang et al. as being suitable for what-if analysis and risk analysis as a tactic-level decision tool, meaning that it helps make decisions on initiatives that will link overall strategy to daily operational decisions. The tool has the capability to link to external optimization tools as well as other tools that help make strategic and operational level decisions. To improve model scalability and performance of the simulation, the tool keeps simulation data in a database that can import and export data using Excel or CSV files, although it appears to be up to the user to decide what database to use. Templates are provided for defining different supply chain elements through a drag-and-drop type approach. For example, a network design template exists that contains predefined elements to represent distribution centers, warehouses, transportation routes, etc. that can be used to define the supply chain network, with data tables available to enter data for each element. Input parameters can be made time dependent such that changes in the network or demand, for example, can be defined to change over time during a simulation run. For products in the system, the tool uses a Bill of Material approach for input data to define the relationship between levels of components. Other input data consists of demand, cost, capacity, lead time, and policy, among others. Cost data in the model consists of "one-time transition cost, fixed cost and variable cost" associated with a defined time period, including direct labor costs, in-direct labor costs, energy consumption and other manufacturing related and transportation related costs that are tracked and aggregated in the model. The tool allows modeling of resources such as workers, trucks, equipment, etc. In general the tool presents a generic simulation platform used to evaluate performance measures and improve supply chain operations. Although it is touted as an effective tool for risk analysis it is not entirely clear what methods or approaches it explicitly provides beyond what typical simulation tools provide for improving risk management.

Other tools exist that do not use simulation but provide information relevant to managing supply chains for disruption risks by helping to monitor the supply base. Several tools available from Dun & Bradstreet (D&B) represent a variety of tools that aim to help better understand risk of disruption in supply chains by helping companies better understand their suppliers. D&B provides several commercially available reports that rate suppliers using proprietary evaluation tools. One example is Supplier Evaluation Reports (SER) available for purchase from D&B ("Dun & Bradstreet Supplier Evaluation Report" 2011; Ellingson 2011). SER provides an assessment of the level of risk involved with doing business with a specified supplier based on an analysis of the supplier company that includes consideration of accidents or catastrophes that could affect the supplier's operations. SER also provides a Supplier Risk Score that indicates the likelihood of the supplier going out of business which could cause a disruption in supply. D&B also offers a tool called Supplier Risk Manager (SRM) that is designed to "give you a 360-degree view of your risk exposure – anywhere, anytime, any supplier" ("Supplier Risk Manager" 2011). SRM helps certify and track suppliers as well as monitor and measure various supplier risk factors throughout a program life-cycle to provide real-time data and proprietary predictive risk indicators to help recognize supplier related risks before they result in negative impacts on supply chain performance. SRM also provides a D&B maintained database that tracks corporate linkages throughout the world to help better understand what affect their might be on one's supplier base because of things happening to the supplier's parent company, subsidiary, etc.

3 METHODOLOGY

The methodology used to preliminarily explore the design and evaluate the effectiveness of RSC*Model* in providing the information needed to make risk management decisions that minimize the total cost of ownership of a supply chain is explained in this chapter. As noted in Chapter 1, the method to address the objectives and hypothesis of this thesis is in several parts. As a matter of convenience, the steps outlined for this methodology in Chapter 1 are repeated here:

1. Determine customer needs
2. Assess current technologies and practices
3. Develop a functional specification
4. Develop a prototype discrete-event simulation based tool
5. Do a pilot contextual demonstration
6. Survey users in the pilot contextual demonstration
7. Assess the effectiveness of the tool along three key dimensions:
    - Minimization of Supply Chain Total Cost of Ownership
    - Ease of Learning & Use
    - Comparative Advantages & Disadvantages in Functionality

As noted, portions of these steps are completed in cooperation with other participating individuals and organizations, including the Lead Non-Profit Organization and ProModel Corporation. Two primary parts of the method included, first, the evaluation and comparison of similar supply chain analytical tools and recommendations for the design and future enhancements of RSC*Model* based on the literature review, and second, the development of evaluation procedures and survey instruments to facilitate and improve the gathering and reporting of empirical information from demonstration feedback from practicing supply chain professionals given exposure to the RSC*Model* tool. Explanations of the methods used and actions taken to address each step are provided in this chapter.

3.1 Determining Customer Needs

As stated, the preliminary research and initial concept and premise for the development of RSC*Model* were completed by the Lead Non-Profit Organization. In order to further refine the initial concept, help guide its development, and provide a contextual test case for the RSC*Model* tool, the development team partnered with a military equipment manufacturing group operating within the Department of Defense. This government "buyer" organization agreed to participate in the pilot project and provide access to contacts and information about a set of manufactured parts and their related supply chain to act as a test case for the development effort. The team initially looked at the family of parts and after discussions with the buyer organization ultimately elected to use one specific part and its supply chain as the test case. The part provided a supply chain with an appropriate level of complexity to provide a simple and straightforward yet instructive example for this phase of the project.

A set of surveys were developed by the Lead Non-Profit Organization and reviewed and revised by the development team in order to gather the information needed to define and model the sample supply chain and develop a prototype tool. One survey was developed for the partnering government organization acting as the target or 'buyer' organization in the sample supply chain. Another survey was developed to gather relevant information from a set of suppliers identified in the supply chain that provided a small but representative portion of the supply network. These surveys also sought to provide insight and gain a better understanding of customer needs and what capabilities and functionalities potential users and organizations would want to see in such a tool. One of the main concepts from the outset of the project was to create a tool that would be useful and useable by Supply Chain or Program Managers. As such, the surveys also sought to provide input to guide the design of the prototype and proof-of-concept RSC*Model* tool. One additional benefit of the development of the buyer and supplier surveys is their representation as a preliminary method for gathering the information that is necessary to use the tool. The survey administration process itself also provided insight on the required data and information gathering effort.

Once the surveys were developed by the team, representatives from the Lead Non-Profit Organization administered the surveys and reported on gathered information and feedback. An overview of the pertinent details from the reported findings is provided in Chapter 4.

3.2 Assessment of Current Technologies and Risk Management Practices

The review of literature provided in Chapter 2 plays an important role in the methodology for this thesis as it aims to provide a preliminary evaluation and guidance for development of a new risk management tool. The literature review explored concepts of risk and the risk management process to provide an important foundation for viewing and understanding risk in supply chains and current supply chain risk management methods. From the review, basic definitions of supply chain and supply disruption risk were provided which, as described, is an important step in any analysis of risk. The review also helped guide the development of a conceptual and working view of risk not common in the literature. This view is provided and explained in Chapter 4 and ultimately provides a useful frame of reference for understanding where RSC*Model* fits and can contribute to the risk management process. Based on the literature review suggestions are provided for further enhancement of the RSC*Model* tool.

3.2.1 Alternative Tool Assessment

The literature review also provided information on common approaches and types of risk analysis tools as well as a few specific tools used in commercial practice or detailed in the literature. It was intended from the preliminary design concept developed by the Lead Non-Profit Organization that RSC*Model* would be a simulation based tool. The literature review aimed in part to assess the appropriateness of simulation for the objective of the tool and explore other potential approaches. The review of a sample set of risk management tools also provided the means to assess and compare RSC*Model* with other current tools.

It was not possible to review all possible types or specific tools, but a common set of approaches for supply chain risk management identified in the literature were reviewed and specific tools were selected based on information availability, references in the literature, and personal experience of the author to present a representative set of tools used in practice or promoted in the literature as effective for risk management. A specific focus was made on tools promoted or viewed as providing potential for improving management of supply disruption risk. Since some of the tools are commercial and proprietary, the information available for the review is at times limited and focused on promoted capabilities and features. Where possible, information related to the use of the tool was also explored such as user interface approaches, data gathering and input, and data and analysis output reporting. Information from the literature review is used in Chapter 4 to further analyze the tools and qualitatively compare their capabilities, strengths, and potential contribution to the risk management process with that of the developed RSC*Model* tool. Information on other tools and methods is also used to develop recommendations for development and improvement of RSC*Model* as an effective tool for management of supply disruption risk.

In addition to tools reviewed based solely on promotional and academic literature, three other tools being developed under government funded projects for risk analysis were evaluated, which included RANGER, PrimeMap and PrimeSupplier. These tools were examined specifically to assess capabilities and functionality useful for disruption risk management and to determine potential for future integration with RSC*Model* to leverage expended resources and to limit overlap of effort. To address these assessment goals, there were two primary goals for the information gathering effort for these tools. First, was to identify what information each tool requires for inputs and provides as outputs, and second, to conceptually identify potential linkages between RSC*Model* and the other government tools, which also included preliminarily identifying technical capabilities available for integration. Available literature for each of the tools was sought out and reviewed by the author to provide a basis for understanding and evaluation of the tools. The review of available literature also identified gaps in understanding and guided the development of a set of assessment questions to gather additional information. The assessment questions were reviewed and revised several times within the RSC*Model* project team and then sent to project managers for the other government funded tools prior to teleconferences held with those managers. The assessment question were provided in an effort to improve information yield from the meetings by helping the managers prepare and understand what type of information the team was seeking and ultimately guided the reporting of finding. The questions submitted to the project managers are in included in Appendix C.1 and D.1.

Following the conference calls, the author of this thesis and other participating individuals collaborated to develop assessment reports for each tool as well as diagrams outlining the input and output information of each tool and a proposed integration approach for the tools. This additionally provided another means to evaluate where RSC*Model* fits in the world of supply chain analytical tools. The prepared diagrams are provided in Appendix F and the assessment reports are provided in Appendix C.2 and D.2.

3.3 Functional Specification

After the initial concept for RSC*Model* was developed by the Lead Non-Profit Organization and customer needs gathered and assessed, the project team moved on to develop a functional specification to guide the development effort for creation of the proof-of-concept and prototype simulation tool. Prior to a formal functional specification, the Lead Non-Profit Organization team developed a "storyboard" to outline the basic use case intended for the tool. Following review of the storyboard by the team, including the author of this thesis, a functional specification was then developed and also reviewed, with input gathered from team members, and revised to define the scope of work and define a set of functionalities and capabilities to be included in the prototype tool. Ongoing input from team members during the development effort also guided evolution of the functional specification and tool design based on input from project sponsors, and from insights, findings, and discussions among team members. The main development concepts and specifications from the functional specification are provided in Appendix E.1. Additional recommendations for future enhancements of capabilities and functionality of the RSC*Model* tool based on the findings of this thesis are provided in Chapter 5.

3.4 Prototype Tool Development

Actual development of a proof-of-concept and prototype RSC*Model* tool was a lengthy and iterative process spanning several months. The tool was created using ProModel Corporation's flagship simulation product and the actual coding and creation of the tool was completed by ProModel employees participating on the project. Presentations on the development effort were periodically presented to the team and project sponsors, and as noted, feedback and input were provided to guide the remaining development effort.

3.5 Pilot Contextual Demonstrations

A fundamental part of this thesis from the outset was intended to be the gathering of empirical data on the effectiveness of RSC*Model* in providing better information to manage disruption risk and lower supply chain TCO. The initial goal was to use the prototype RSC*Model* tool in a formalized, hands-on evaluation procedure with program or project managers or other practicing supply chain "experts" using RSC*Model* and other currently used methods or tools to formulate management strategies for dealing with theoretical, though realistically validated supply disruption scenarios. The scenarios provided to the participants were intended to be based on the sample supply chain used during development of the RSC*Model* tool. In this approach, each expert would be presented with a predefined disruption risk scenario for the existing supply chain and asked to indicate the approach or solution (i.e. supply chain configuration and coordination decisions, etc.) he would use to manage the risk based on analysis performed with current tools or techniques. The same would then be done using the RSC*Model* tool and the results for TCO of the supply chain compared.

This evaluation procedure would act as a controlled pilot implementation where data could be gathered about the key dimension of "effectiveness" outlined in the methodology; namely, the ability of managers to mitigate risk and minimize TCO of a supply chain and the ease of learning and use of the RSC*Model* tool. The approach would also include a follow-up survey for the participating managers following the experimental procedure to gather additional information to better and more precisely gage the effectiveness in quantitative and qualitative terms. A preliminary and proposed outline for this evaluation method and possible administration procedures developed by the author is provided in Appendix A.2. A more concise proposal for this evaluation effort was submitted to the RSC*Model* project managers and is provided in Appendix A.1.

Unfortunately it was not possible to carry out this more robust approach for evaluation of RSC*Model* at this phase of the project. Not only was this approach difficult as it requires finding and gaining commitment from several managers willing to participate in the evaluation, the feasibility of administering the hands-on approach with various persons from industry was essentially eliminated due to the limitations, access restrictions, and time consuming procedures and policies imposed on the project from the sponsoring government agency. This disappointing development of the project reduced the amount of empirical information that was able to be obtained for this preliminary assessment. This thesis instead relies on feedback gathered following several contextual demonstrations of the RSC*Model* tool to various managers and practicing supply chain professionals. The contextual demonstrations included the model of the actual supply chain from the partnering "buyer" organization with a sample data set for model inputs based on the sample supply chain as well as a discussion of model capabilities and an overview of output reports provided by RSC*Model* including example findings from the sample data set. The author encouraged through feedback on demonstration models and materials, the development of instructive and illustrative scenarios as examples to demonstrate the various capabilities of the RSC*Model* tool. The tool was presented and demonstrated several times to the project sponsors managing the project as well as to managers from the partnering "buyer" organization in onsite visits and to various supply chain professionals at several Department of Defense related technology and manufacturing conferences. These provided opportunities to gather feedback from participants to use as part of the preliminary evaluation provided in this thesis.

3.6 Gathering Empirical Information from Demonstration Feedback

With the more robust evaluation procedure not being feasible, the effort to gather empirical information for evaluation turned to a more concise survey instruments to guide evaluation based on feedback from contextual demonstrations of the tool. Brief survey instruments were developed in an iterative process with development going through several revisions with reviews by other project members and leaders.

3.6.1 Surveys and Survey Design

The use of surveys was pursued as an important part of the methodology for collecting feedback and data from the supply chain professionals participating in pilot contextual demonstrations. There were two basic versions of surveys created throughout the course of the project. Copies of these surveys are provided in Appendix A.3 and A.4. The original survey was more complex and was aimed at gathering information on the user experience and opinions on effectiveness and design of the tool. The survey was developed to encompass various possible means of exposure to RSC*Model*. A review of literature on best practices on survey design was used to guide the survey development.

As an important first step in the feedback survey design (Sampson 1999), the goals and objectives for the feedback of the survey were considered. The goals for the survey were driven by the thesis objective and methodology. Each question in this survey was mapped to a stated objective. These are included in the copy of the survey provided in Appendix A.3. Following Sampson's framework for feedback survey design, the functional target is primarily the design and operational aspects of the RSC*Model* program. The goal was to gather information about the effectiveness in terms of value and usability of RSC*Model* and ultimately provide information that could be used to determine how to produce and deliver a superior product. As such, the objective for the survey is to serve both immediate needs to evaluate the current effectiveness of RSC*Model* as well as provide feedback that in the long-term can help improve RSC*Model*. The survey was also designed with response bias in mind. The intention was to "actively" administer the survey by giving the survey to participants and encouraging their response which helps reduce response bias. The survey was also designed and evaluated with the time and effort requirement for the responding supply chain professional in mind. The aim was for the survey to be both extensive and complex enough to gather as much pertinent information as possible to meet the objectives but short and inflexible enough to ensure that accurate and quality responses would be received in a timely manner. To keep the survey simple and provide a means to quantify responses, it was decided to use a Likert scale for responses on the survey in order to keep it simple to answer since the response options are consistent. This approach also provides an appropriate method to "prime" respondents to provide open-ended responses in an additionally provided comments box with each question. The Liker style responses with a descriptive wording scale also help improve response accuracy. As Sampson notes, "[people] are more accustomed to describing their views and feelings semantically (verbally), as is typical of ordinal scales" than numerically on a strict numerical interval scale.

Out of necessity the survey was designed to be an “ex-post” instrument that would be provided for completion after exposure to the tool is complete. In future evaluation procedures, in-process elements would be beneficial to gather responses that are not biased from more recent information and would help reduce a halo effect in responses from either a good or bad overall experience with RSC*Model* or the evaluation method. Following Sampson’s advice, and as stated, the surveys were also reviewed prior to administration by other team members to ensure proper wording for accurate and unbiased responses.

When it became evident that feedback from demonstrations was likely the only method through which feedback would be obtained, the survey was revised and simplified even further with questions reworded and only a three level response scale provided where respondents provide a relative rating response to the survey questions. Otherwise, the simplified survey followed the basic guidelines discussed above. This was delivered to the Lead Non-Profit Organization project managers providing the presentations and demonstrations of the RSC*Model* tool to help guide their gathering of feedback following each event. The ultimate feedback that was able to be gathered is reported on in Chapter 4.

3.7 Assessment of Tool Effectiveness

The method to assess the effectiveness of RSC*Model* along the three key dimension described has been discussed in various parts of the previous sections of this chapter. This step in the thesis methodology is vitally important to address the thesis objective and hypothesis. The methodologies to address each dimension are discussed briefly here.

3.7.1 Minimization of Supply Chain Total Cost of Ownership

The primary concept for RSC*Model* is to mitigate the effects of supply disruption risk by minimizing the cost impact on the supply chain through tactics that enable and optimize their design, assembly, coordination, and ability to quickly reconfigure or reconstitute after a disruption (Peters 2010). Ultimately the goal of RSC*Model* is to improve the quality of decisions that are made in relation to managing supply disruption risk to minimize impact on TCO of the supply chain. As described, the goal of maintaining a 100% service level is a simplifying assumption made with the RSC*Model* tool that limits the assessment of total cost specific to the risk of supply disruption.

As described in the Section 3.5 (Pilot Contextual Demonstrations) above, a robust evaluation procedure was preliminarily developed to help evaluate the effectiveness of RSC*Model* in minimizing the Total Cost of Ownership of a supply chain related to supply disruption risk. The intended methodology for this more robust evaluation procedure was to include questions in an accompanying questionnaire that asks each participating expert to indicate the method used to arrive at the chosen solution (i.e. why and how the solution was chosen), and what he expects the outcome of the solution to be (i.e. the expected total cost). Each expert would then be asked to use the RSC*Model* tool to develop a solution to the risk scenario. The original response of each expert would then be evaluated on a total cost basis with the RSC*Model* tool and compared to the solution developed using the RSC*Model* tool.

As this robust approach was not feasible, the evaluation of this objective turned to more subjective questions included in the described surveys. The surveys were designed to gather respondents' opinion about whether they can more effectively determine how to minimize the cost impact of supply disruption risk with RSC*Model* than with other methods, whether RSC*Model* provides sufficient information to fully understand the cost impact, whether the solution options are appropriate and sufficient to create effective strategies, and whether RSC*Model* addresses the appropriate issues and presents an appropriate process to assess and make decisions about the impact on cost. Ultimately, the limitations of the project left this aspect of the research methodology with little empirical data from which to make inferences specifically about the ability to reduce the cost impact of supply disruption risk.

3.7.2 Ease of Learning & Use

Part of a total evaluation of "effectiveness" of any tool should involve consideration about how easy it is to learn and then use a tool on a systematic basis for decision making. A tool that either has too steep a learning curve or is too cumbersome or difficult to routinely use will face a steep road to adoption and ultimately has diminished effectiveness because its value is reduced due to excessive effort, time, and resources required to make decisions on how to conserve those same things.

As with the last dimension, minimizing TCO, ease of learning and ease of use were both set to be measured and assessed through the more robust proposed evaluation method only to be inhibited through lack of effective avenues to evaluate the measures. A hands-on experience with real users would provide the opportunity to measure the time required to enter necessary information and create the supply chain model and perform evaluations and analysis. Monitoring the experience of users would also allow the measurement of the number of questions each user has when using the tool, after being briefed on standard usage procedures, to help evaluate ease of learning. The method instead turned again to simplified surveys requesting the opinion of potential users on the perceived ease of use of the tool. Ultimately, the feedback received from demonstration participants is used to guide a preliminary qualitative assessment of the stated dimensions of effectiveness in Chapter 4.

3.7.3 Comparing Advantages and Disadvantages in Functionality

As described in Section 3.2 (Assessment of Current Technologies and Risk Management Practices) of this chapter, the literature review for this thesis provides information on a set of generic supply chain management approaches and specific tools. This information provides the basis for a qualitative comparison of the offered functionalities of RSC*Model* and other currently available tools and methods. A primary contribution of this thesis is a set of radar charts prepared to compare RSC*Model* and other reviewed tools for perceived relevance in managing each basic step for effective supply chain risk management as identified through literature review. The discussion around this comparison and the prepared charts are provided in Chapter 4. The ultimate goal of this comparison is to identify potential shortcomings and advantages of RSC*Model* versus other similar tools and methods when used to address supply disruption risk in supply chains.

4 RESULTS

4.1 Perspective on Supply Chain Risk Management

As noted, the literature review provided in Chapter 2 plays a key role in this thesis as an exploratory study of a new tool for effectively managing supply disruption risk in modern supply chains. Part of this study involves understanding what functionality and capabilities such a tool should possess and what design elements and approaches it should use. This includes understanding how it should view disruption risk, and where it fits in the risk management process. Based on the literature review, perspectives on supply chain risk and risk management are proposed that help better understand RSC*Model*'s approach and its potential contribution to the risk management process.

4.1.1 Basic Risk Management Cycle

As described in Chapter 2, there are various models available for risk management, but at a simple level there is a common theme on four basic processes. These primary steps of the basic risk management model were explored and described in Chapter 2 and are shown graphically in Figure 4.1 with simple explanations for each step. This basic model is used later to help understand how RSC*Model* and other tools compare in potential to aid in each of these generally agreed upon phases or steps of the risk management process.

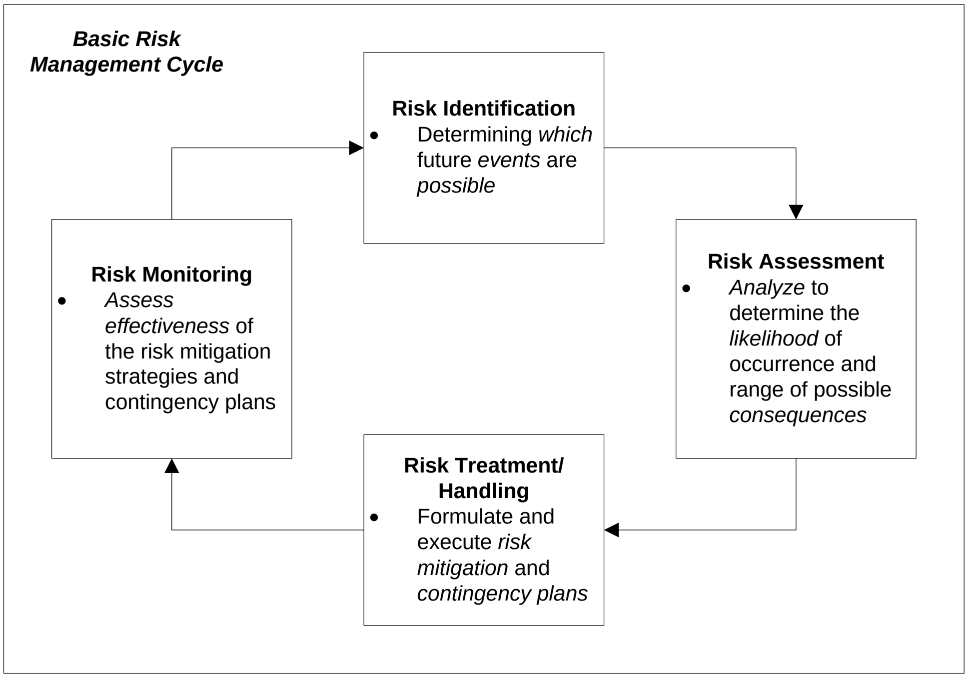

Figure 4.1 – Basic view of the risk management cycle

4.1.2 Alternate View of Supply Chain Risk

In Chapter 2, various views and definitions of risk were explored. Based on this literature review a shortcoming in most views and discussions of risk is identified and an alternate view more appropriate for understanding supply chain related risks is proposed. As described, the traditional view of risk is the product of *probability* and *consequence*. The implication is that risk has two parts, the probability of a negative event occurring and the corresponding severity of consequences of that event if it occurs. When viewing disruption risk in supply chains, however, there is a limitation and generally unaddressed oversimplification with this view that does not provide an adequate framework for analysis of supply disruption risk. The traditional view glosses over the fact that there are actually two components of a risk event. As explained there is the possibility that the event will happen, which is typically represented by a probability, but there is also some related “magnitude” with which that event occurs. Another way to view this distinction from the point of view of severity or consequence is that any risk event has both an immediate consequence, the “magnitude” of the event itself, as well as extended consequence, the resultant “impact” of the event occurring. Often these concepts of magnitude and impact are mixed. This view proposes that for effective analysis of risk they need to be viewed and treated independently. This distinction is particularly important in understanding, representing, and analyzing supply disruption risk. This proposed view of risk is represented visually in Figure 4.2. Based on this concept, the definition for supply chain risk can be updated correspondingly as shown in the figure.

Supply Chain Risk The *probability* that an event of some *magnitude* will occur that results in a loss or undesirable *impact* on supply chain performance.

Probability	Magnitude	Impact
Potential or likelihood of occurrence of risk event within some time frame • *What is the likelihood the risk event will happen?* • *Where is it likely to happen?* • *When is it likely to happen?*	Magnitude of risk event (degree and duration) • *How long will the disruption last?* • *Who/What (which suppliers, what parts) will be affected?*	Loss or undesirable outcome on performance from extended consequence of risk event • *Δ Total Cost of Ownership (TCO)* • *Δ Service level*

Figure 4.2 – Proposed view of supply chain risk

To illustrate this concept, for a supplier in the supply chain there is some probability that an earthquake will strike at the site of the supplier facility. Knowing that an earthquake struck the facility alone is not enough to understand the impact. The earthquake also hits with some “magnitude” which ultimately affects the nature and extent of resulting negative consequences. The causal view of risk presented by Fenton and Neil (2006a; 2006b) is also important when combined with this concept. The consequence of an earthquake may be the disruption in the capacity of the supplier to produce and deliver goods. The duration of this disruption depends on the magnitude. It also depends on what controls, or in other words what mitigating conditions were in place prior to the risk event (the earthquake) and what further mitigating actions (contingency plans) take place following the occurrence of the risk event. Looking further down the causal chain, viewing the disruption as the event, you again need to know the magnitude, or duration, of the disruption as well as any mitigation steps to determine the impact of the event. This view also implies that the basic "risk assessment" step in the outlined basic risk management process actually has three important parts related to assessing each of these three aspects of risk.

This is not an entirely new concept and many authors allude to such an approach, but rarely is it explicit. A conceptual three-step approach for risk assessment from Steele and Court (1996) presented in Chapter 2 includes a similar distinction, suggesting that the probability of the risk event be determined followed by an estimation of the likely problem *duration* and investigation of the *business impact* of the risk event. This similarly indicates that the magnitude of the risk event, in this case in the terms of duration, in addition to the probability is needed to fully determine the consequences through evaluation of the impact. When defining a view of risk this three-component view, however, does not appear to be common in the literature; yet, it is an important view when analyzing disruption risk.

4.2 Evaluation of Current Risk Management Technologies and Practices

As a current area of interest for the supply management discipline and for most companies, lots of tools for supply chain management are described as being useful for risk management. It is often not well described exactly what capabilities these tools provide and understanding how they could be used to improve risk management can be difficult. An overview of a set of various tools and approaches was provided in Chapter 2. The appropriateness of different approaches as the basis for a disruption risk management tool and the perceived potential for contribution to the basic steps in the risk management process for the specific tools reviewed are explored further here.

Based on the information gathered about different supply chain disruption risk management approaches, discrete-event simulation (DES) and optimization are ideally suited as the basis for a tool like RSC*Model*. DES is already widely accepted as a tool of choice for making supply chain related decisions. DES permits realistic, dynamic representations of complex systems with various interdependencies and variation in the timing of events. The focus of RSC*Model* to evaluate the impact on supply chain performance, specifically cost, of supply disruptions and mitigation strategies is well suited to the use of DES since it can represent the actual functioning of a system at an operational level. DES based tools in general, then, appear to be best suited for risk assessment, in terms of analyzing consequences of risk, and risk treatment, through analyzing and identifying appropriate options for dealing with risks.

Other approaches also have merit but are not as well suited for the primary focus of RSC*Model*. Benchmarking is a useful tool for identifying potential problems in a supply chain and therefore could be useful for risk identification. It can also help identify best practices for mitigation strategies that could guide preliminary development of risk management strategies and provide and track good metrics for risk monitoring. It does not, however, provide predictive analytic capabilities to see the probable effects that any strategy may have on the actual system. Similarly, mapping and cause-and-effect approaches provide appropriate methods to help identify root causes of problems, such as the triggers for supply disruption risk events and therefore can be helpful for risk identification. They can also be used to make logical assessments of what the consequences of various situations and conditions might be, but they do not provide robust means to quantitatively assess the full impact of risks or validate the effectiveness of mitigation strategies. Bayesian network approaches can help provide probabilities for disruption risk events but provides only a static analysis and doesn't provide a good way to assess the timing of events and therefore the ability to predict the impact of risk events is limited.

Based on the overviews of specific tools provided in Chapter 2 it is also instructive here to make preliminary assessments of the individual tools' capabilities and perceived relevance for contributing to the four basic risk management process steps. In order to help comparatively assess the capabilities of the various tools reviewed, a preliminary qualitative assessment of tools is made here and mapped on a simple radar chart for each risk management process step. Based on the information that could be gathered for each tool and the literature based description of each basic risk management process step, each tool is ranked as having (2) "high perceived relevance," (1) "low perceived relevance," or (0) "no significant perceived relevance" for each step. Without formal, personal use and evaluation of the tool, this ranking of perceived relevance is based on how applicable each application is promoted or intended to be and not on how well the functionality is executed or presented in an easily useable manner.

The other government funded tools (RANGER, PrimeMap, and PrimeSupplier) were reviewed most extensively and the investigation into integration potential with RSC*Model* revealed where the tools appear to fit best in the risk management process. With the abilities to gather supplier data and provide a visualization of the supply chain, PrimeMap's capability seems to be best suited for risk identification efforts. In particular, PrimeMap helps identify risks from disruption from various natural disasters. While it does not provide risk identification capabilities for a wide variety of risks, it does have high relevance for some important ones. PrimeSupplier is similarly focused primarily on risk identification, specifically for supplier financial risk, operational risk, and other "readiness" factors that relate to supply chain risks. Both tools also have some relevance for risk assessment, providing quantified risk factors and visualizations of disaster potential, but lack systematic methods to develop probability estimates for risks which are needed to assess their impact on supply chain performance. The tools can help determine the potential magnitude of risk events, such as natural disaster "strength" or severity of supplier problems leading to disruption, but again, they lack the capabilities to assess the final impact. As such they also provide little relevance to develop risk treatment and handling options. They could help identify suppliers and supply chain network configurations that have lower potential for risk, such as identifying suppliers with lower financial risk or those located in geographic areas less prone to natural disasters, but they offer little guidance for validating the effectiveness of strategies for mitigation. These capabilities are likely better suited to monitoring the risk situation by tracking current information on risk factors for suppliers in the supply chain.

The other government funded tool reviewed, RANGER, has a different focus. In the conceptual integration diagram prepared, RANGER generally sits "below" the Prime tools discussed above, implying that its strengths lies in a later risk management process step. Indeed, based on a Bayesian network approach, RANGER provides a systematic method to calculate resultant risk probabilities making it ideally suited to aid in the risk assessment phase. While it still lacks capabilities to fully understand the timing, magnitude, or impact of risk events it does provide a highly relevant piece of the risk assessment step. The risk element taxonomy developed for RANGER also provides an important causal risk map that can help identify sources of risks, but it does not appear to provide a systematic way to determine the initial probabilities used to find later probabilities. It does provide some relevance for risk treatment and handling by providing a way to calculate the effect on risk probabilities of controls and mitigants and tracing risks back to root causes, but again it lacks the means to determine resultant measures of the effect on performance, providing no readily apparent means to evaluate the cost impact. For example, RANGER could help find the probability that a shipment will be late but is less well suited to determine just how late and what impact that will have on supply chain performance. RANGER could contribute probability calculations to monitor changes following implementation of risk management strategies. Based in this brief assessment, the Prime tools and RANGER are mapped for relevance to each risk management process step as shown in Figure 4.3.

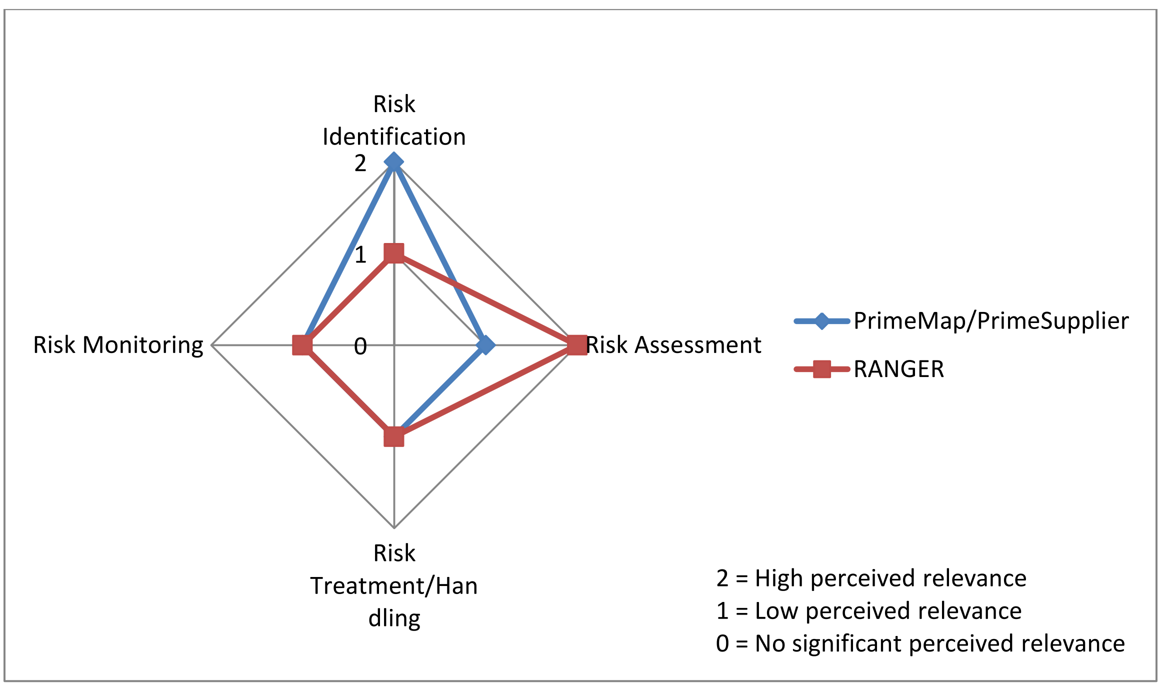

Figure 4.3 – Perceived relevance of PrimeMap/PrimeSupplier and RANGER

Supply Chain Guru (SCG) is a simulation based tool that finds its strength in assisting decision makers to optimize the supply chain network design for improved supply chain performance. This focus, combined with the ability to introduce disruptive events and analyze effects on the supply chain and formulate various alternative network options, makes SCG most relevant for finding appropriate risk treatment and handling options through optimized configuration and coordination decisions. It appears that SCG can also provide relevant insight into the consequences, or impact of disruptive events in the supply chain as well. As stated, however, it does not appear to have a systematic way of identifying disruption risk, except that its detailed modeling capabilities could be used to identify potential bottlenecks or constraints that may lead to temporary disruptions, and the use of Google Earth as a visualization tool allows for some analysis of weather and other natural disaster related concerns. As a predictive analytic simulation tools its focus is on predicting performance and not on tracking performance, which would provide little if any relevance for risk monitoring except that near real-time data could be used in the model to assess current conditions.

Without going into details reviewing the information provided in Chapter 2 concerning the remaining tools, each has areas of strength as well as limited relevance for some steps. As other simulation based tools, the "typical proprietary simulation tool" and IBM GBES are similar to SCG in functionality but are seemingly less robust. Like most proprietary simulation models, the "typical" tool reviewed here is significantly less flexible than SCG. Therefore, while it can still be highly relevant to the risk treatment step, the process of formulating and testing risk treatment strategies is less effective. As with most proprietary DES-based tools, making modifications to the configuration, coordination, and other operating policy decisions in the model requires a much more involved process. It can also help assess the impact on disruptions, making it relevant for risk assessment, although the tool was originally only concerned with schedule and service and did not include other performance measures such as costs. As a benchmarking tool, SCOR includes those strengths related to benchmarking approaches, namely providing metrics and other key performance indicator measurements and comparisons which make it most relevant for risk monitoring and risk identification. Also, as described it can help improve configuration decisions and develop new design strategies, but lacks methods to predict the actual effects and impacts in a real, dynamic system. The perceived benefit of simulation tools based on the SCOR model is that they could maintain the benefits of the static SCOR model in risk monitoring and risk identification while adding the typical benefits of simulation in formulating risk treatment strategies, although the effectiveness compared to traditional simulation approaches remains in question. SCOR based tools are also focused on business processes at a higher level than those that can be included in some other simulation tools making it difficult to create operational level strategies. D&B type tools primarily provide capabilities to monitor the supply base for risks and therefore have relevance primarily for monitoring and identification and could contribute to assessing the probability and magnitude of potential disruptions or other risks. The perceived relevance for these tools is presented in Figure 4.4.

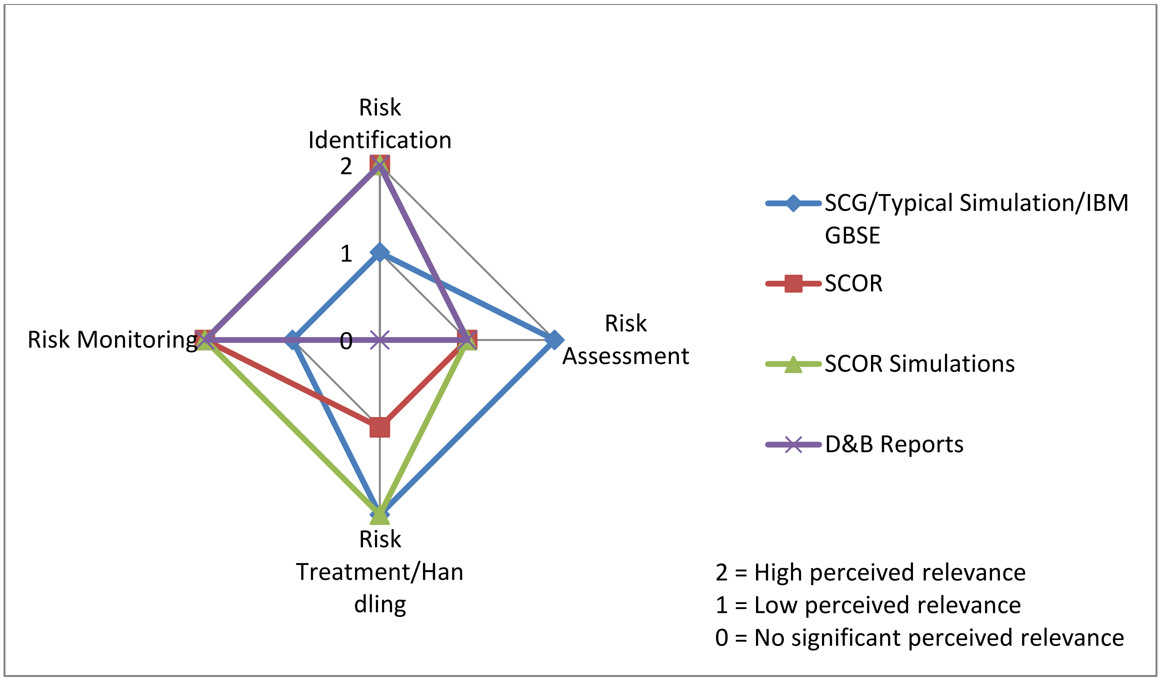

Figure 4.4 – Perceived relevance of sample supply chain risk management tools

4.3 Design of RSC*Model*

The design concept of the RSC*Model* tool was developed through a collaborative process. With influence from customer needs gleaned from participants in the sample supply chain, feedback from project sponsors, as well as input from the RSC*Model* project team, a preliminary design specification for the tool was developed.

4.3.1 Customer Needs and Findings from Supply Chain Survey

An overview of the buyer and supplier survey process and the relevant feedback and findings from their administration is provided here. One of the goals of the surveys was to get information needed to model the sample supply chain. Information on the configuration and coordination details of the supply chain network was obtained including which subcomponents each supplier produces and a Bill of Materials outlining the hierarchy and relationship of parts and suppliers relative to the final "buyer" organization and its finished product. Information on demand quantities and patterns, inventory levels and policies (including safety stock), supplier lead times, ordering and production conventions (make-to-order, make-to-stock, etc.) and costs were also gathered. Cost-related information gathered through the surveys provided not only specific cost data but also information on when and how costs are incurred in the sample supply chain. This provided the basic data that would be need to build a model and run a simulation. The supply chain information also guided how data would be entered in the RSC*Model* tool. Specifically relating to costs, the information from the surveys directly resulted in the inclusion in the model of a method to assign not only piece price costs but also other incurred costs based on other criteria such as costs for tooling, engineering, etc. that may be applied on either a per unit, per Purchase Order (PO), or one time basis.

The survey also found that Total Cost of Ownership does not currently play an important role in sourcing decisions in the sample supply chain or at least the concept is not used in a robust manner. The buyer organization, for example, indicated that it currently looks at the piece price, which only relates to direct costs such as engineering and machining costs. Supplier health was noted to play at least some role in sourcing decisions with some dollar limits imposed on orders to certain vendors. The surveys also revealed that bringing on a new supplier can be a complex process with multiple criteria that alter the selection and acquisition process.

Details about supplier capacity and flexibility in production quantity were also gathered. This information was primarily for the RSC*Model* agility analysis, although the ability of a supplier to increase production could also be used in disruption risk analysis as part of a mitigation strategy. In dual or multi-sourcing situations when a supplier goes down, another supplier sourcing the same part may be able to "surge" and produce above its baseline rate in order to pick up some of the slack. The surveys also gathered additional information about suppliers that could be helpful in determining how risky a supplier might be in terms of susceptibility to disruption such as the percentage of overall business from "buyer" orders, length of time supplying parts for the "buyer," and production constraints. More detailed information about supplier's internal processes and sourcing decisions and conditions were asked in the survey but little information was gathered here and RSC*Model* was ultimately created to model at a higher level where this type of information was not necessary.

The surveys and their administration process also provided a representation of a preliminary method for gathering the information that is necessary to use the RSC*Model* tool. To model any supply chain, information and data about that supply chain must be obtained to create a valid representation of the actual supply chain. Not only do the surveys act as preliminary guides as to what questions and data might need to be gathered, the survey administration process itself also provided insight on the required data gathering effort. Of seventeen suppliers identified in the sample supply chain, seven were chosen by the RSC*Model* team as critical and targeted for supplier survey administration. Of these seven suppliers, on-site interviews to gather survey information were completed with four suppliers. The remaining three suppliers were either reluctant to provide information, never responded to a survey request, or failed to deliver on an agreement to personally complete the survey. This survey administration process alone provides evidence of the non-trivial time, resource, and effort required and often the difficulty there can be to get the information needed from suppliers for a supply chain model.

Although on-site visits with face-to-face interviews with suppliers may not always be required to gather necessary information, in the case of this project it was seen as advantageous to get as much information as possible for the proof-of-concept tool. Initial model development for supply chain analysis may often require similar efforts. The problems with getting some suppliers to respond or provide data as seen in this project can often be another major concern for scenario development and analysis. The personal experience of this author with development and use of another supply chain modeling and simulation tool in an industrial setting reaffirms the evidence that gathering necessary information from suppliers can be difficult and poses a major hurdle for successful use of the tool. The information being asked for and relationships and conditions related to specific suppliers also influence the ease with which information can be gathered. Those suppliers who were willing to participate in on-site interviews were found to be open and willing to answer all of the questions outlined in the supplier survey.

The survey administration experience also revealed that information gathering from smaller suppliers was generally easier than for larger companies. The survey administration team found that, generally, smaller suppliers had one person who was able to answer all survey questions about various aspects of the product produced. At the larger suppliers, however, the primary contact did not always have the breadth of knowledge to answer all questions related to the product. This is an issue that leads to more time and effort required for data gathering.

Ultimately, the information from the surveys helped drive many of the assumptions about the model behavior described in the functional specification. Also as noted, some of the information gathered was related to customer needs and desires. Inferences about customer needs for capabilities and functionality desired in the tool also contributed to the development of the basic design concepts outlined in the next section (4.3.2).

4.3.2 RSC*Model* Functional Specification

The functional specification developed by the RSC*Model* team before serious development began on the disruption risk analysis capabilities of RSC*Model*, included several design elements intended to be included in the RSC*Model* prototype based on suggestions gathered through the buyer and supplier surveys as well as other suggestions inspired or offered by RSC*Model* project participants.

Since the RSC*Model* tool was intended to be useable by supply chain or program managers with no modeling experience as well as provide a reusable framework to allow for easy adaptation for future analysis, several design elements were aimed at satisfying these requirements. One suggestion from persons in participating organizations indicated that "a simplified user interface that allows scenario based analysis is optimal." Based on this suggestion, the prototype tool was to be created with the ability to run any user defined scenarios, within tool constraints, with up to three named scenarios being defined as inputs to the model at any one time. The creation of the three scenarios was also to be made easier through the use of user-named "datasets" for each type of data in the model. The functional specification called for the allowance of three different datasets to be defined for each data type in the model, such as defined suppliers, such that scenarios could be created through various combinations of the various datasets. The user could then quickly define, select, and run various scenarios during the simulation. To make the analysis process of various scenarios easier for the user, the capability to include a user defined name or "scenario title" to each scenario was also defined as critical.

Also from the interviews, supply chain practitioners and potential users indicated that "a nodal approach that allows the ability to replicate those nodes beyond the prototype system is a key design element for future scalability." The main concern here appeared to be the ability to reuse model data, such as supplier information, in new scenarios or for new, expanded or otherwise modified supply chain network designs. In other words, "supply chain configuration and reconfiguration capabilities should leverage the nodal approach to network design in the model." This approach would also allow for easier expansion, or scalability, of tool capabilities during future development.

The tool was also to provide a user-friendly interface to allow for easy addition of suppliers, parts and other items relevant to the analysis. The design therefore called for Excel to be used as the primary user interface. Excel allows for easy data entry and is a widely used and understood spreadsheet application. A logical sequence of data entry tabs in the Excel interface was also defined as desirable for ease of use. To make the data entry process easy for supply chain or program mangers it was also determined that required data should be entered in a form and format that is familiar and accessible to these users. It was therefore determined that the demand signals from the focal "buyer" firm that drive the supply chain model would be entered in the form of purchase orders (PO). While not part of the original design specification, the use of a "Bill of Materials" (BOM) approach to define the hierarchy of components in the supply chain was also determined to be desirable.

Various assumptions and delimitations were also included in the functional specification to limit the scope of the project for the proof-of-concept and prototype tool. The scale of supply chains able to be analyzed by the tool was limited in the functional specification to allow flexibility in analyzing the sample supply chain while not attempting to provide a solution suitable for any size supply chain imaginable. Sixteen total suppliers can be defined with up to twelve "active" suppliers making up the current supply chain network in the model. The extra, non-active suppliers can be defined to allow flexibility in designing other scenarios and to define possible replacement suppliers used in the event of a disruption. Capabilities for stochastic modeling were also specified to be included where the ability to model random variation in duration and timing of events would be desirable. To limit complexity in development, the prototype tool was specified to make no attempt to directly interface with any other databases or applications.

Specifications particular to the capabilities for analyzing supply disruption risk in the supply chain were also specified. The tool was specified to look at only two types of disruptions, permanent or temporary, in both cases being possible to only represent a 100% elimination of supplier production capabilities for the specified time period. Permanent disruptions would permanently remove the supplier from the supply chain, and a temporary disruption would represent the supplier being unable to produce for a specified period of time after which production would be restored to pre-disruption levels. The research and development team also determined a set of possible approaches for handling risk to be included in the tool. These were to represent the possible options in creating recovery and mitigation strategies for supply disruption risk. These options included: carrying inventory, redundancy of suppliers (dual/multi-sourcing), supplier's with access to knowledge base (which reduces time to bring on line), supplier capacity retention, and inventory on consignment.

Various output performance metrics and pre-defined graphs were also defined in the functional specification. These included tracking and reporting the Total Cost of Ownership (TCO), supplier inventory levels, service level, production levels, units produced, as well as a supplier event log to track events occurring during the simulation.

4.4 Prototype RSC*Model* Tool

Based on the evaluation of customer needs and ultimate design specification, a working proof-of-concept and prototype simulation tool, RSC*Model*, was developed. A basic overview of the developed "predictive analytic" supply chain analysis tool is presented here. As described, the tool was designed with the intent to help determine the most cost-effective management strategy for dealing with supply disruption risks. Although the prototype tool was intended for the analysis of a specific sample supply chain, the tool designed is intended to be applicable for future analysis of other supply chains.

RSC*Model* was built on ProModel Corporation's discrete-event simulation technology and uses Microsoft Excel as the primary user interface and data input mechanism. In analyzing supply chain risk, RSC*Model* uses the discrete-event simulation and stochastic/Monte Carlo modeling capabilities of ProModel software to assess the ability of a supply chain to handle a disruption in supply, which is ultimately an assessment of supply chain resiliency. The disruption risks that can be include in the model and may cause a disruption in supply could be from any event or real world phenomenon such as political unrest, financial failure, natural disaster, labor issues, etc., that could either temporarily or permanently shut off supply from a supplier. The prototype tool ultimately, however, is not concerned with the actual source of the disruption event. Thus RSC*Model* simply accepts the probability and severity, in terms of duration, of any such event and does not provide a systematic way to determine these values. RSC*Model* simply allows a probability of supplier failure during a specified (and repeating, in the case of temporary disruptions,) time frame and a user defined severity for the disruption defined in terms of time the supplier is unable to produce or deliver goods. RSC*Model* uses these values in order to evaluate the resultant impact on supply chain performance, including total cost, by dynamically simulating different defined supply disruption scenarios. Figure 4.5 illustrates how the user defines, in RSC*Model*, when a disruption may occur (probability within a time period) and the expected duration of the disruption (either permanent, or a defined temporary duration) and how this approach compares to the proposed view of supply chain risk presented in Figure 4.2. The simulation of disruptions is intended to help find the optimum supply chain management strategy based on total cost of ownership, and also reports other measures such as service level in addition to other production related measures.

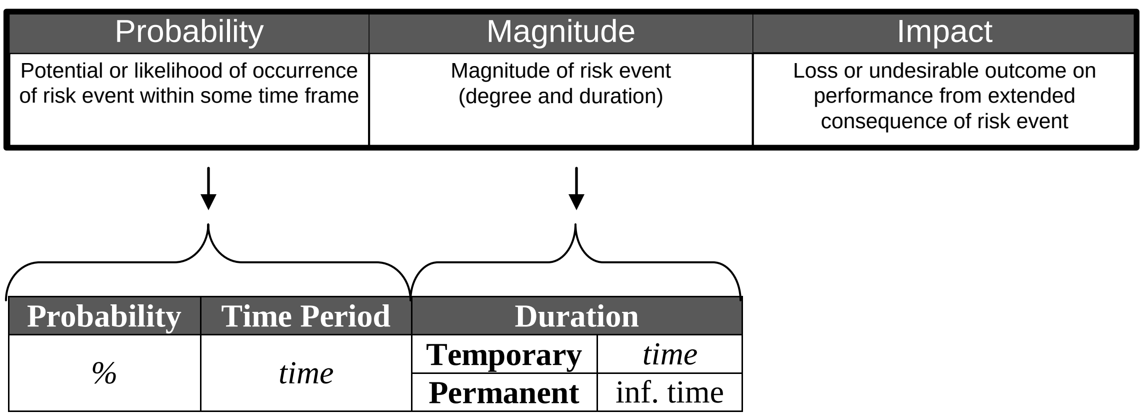

Figure 4.5 – Defining supply disruption risk in RSC*Model*

The intended design of RSC*Model* was to provide two ways to simulate and assess alternative strategies for managing risk of supply disruption in supply chains. Up to three different scenarios involving disruption risk in a supply chain and/or risk management strategies can be evaluated through an "analysis" run mode. As described in the functional specification, scenarios can be created through different combinations of three possible datasets that can be combined for different data types. Not all data types in the model, however, can be mixed and matched in this manner. Each of the three possible scenarios is linked directly to a specific supply chain network structure and specified supplier relationships as well as defined disruption risks for each supplier. This analysis mode provides the ability to individually assess scenario performance as well as compare performance between the three possible scenarios and was designed to be used primarily when there is a defined strategy or situation the user wants evaluate. The analysis capability essentially provides the ability to allow users to "war-game" supply chain disruptions and evaluate different risk mitigation strategies to achieve the appropriate level of resiliency for the lowest total cost. This capability allows the user to quickly evaluate various risk scenarios and mitigation strategies for cost and other performance measures.

Another intended run mode was for “optimization.” The intent with optimization was to automatically run all possible scenario combinations based on defined datasets to determine the “optimum” supply chain risk management strategy based on available user defined datasets with the principal optimization objective being to identify the management strategy that minimizes TCO (i.e. the most cost effective strategy). This intended optimization capability has not yet been fully implemented in the prototype tool.

The possible “management strategies” in the prototype RSC*Model* tool is limited to decisions on a few key variables that create a potential recovery (contingency) or mitigation strategy for each active node in the supply chain and as well as for supply chain network configuration decisions. Only some of the possible recovery strategies originally specified are included in the current prototype. A replacement supplier and time to begin production can be specified for permanent supplier disruptions. Also, multiple suppliers can be specified for any component, and start-up inventory levels and replenishment policies can be defined. Suppliers can also be defined to be capable of a certain percentage amount of “surge” capacity to produce above their typical baseline rate. This could be used to represent retainer capacity, although the associated cost data and other aspects for such an application does not appear to yet be fully functional.

As the prototype currently does not support or integrate with other databases or applications, most of the required input data must be gathered through buyer and supplier surveys and the expertise and experience of the supply chain or program manager using the tool. This information includes basic supplier information, demand data for baseline purchase order patterns, supplier production capacities, supply network configuration, etc., as well as sourcing cost data such as unit price and other business costs. In its current state, RSC*Model* relies on manual entry of input data across several logically sequenced Excel tabs/worksheets entered through a specified sequence of steps for model and scenario creation. Through ProModel's Output Viewer, or export to Excel, standard and customized reports and graphs of scenario simulation output data, as described in the functional specification, can be obtained using built in variable tracking in the model.

A more detailed product summary report, answering many typical questions that may be asked about RSC*Model* was prepared as part of the effort to assess the potential for RSC*Model* to leverage other government investments and can be found in Appendix E.3. This summary is based primarily on intended functionality per the functional specification. A diagram of the data and information inputs and outputs for RSC*Model* was also prepared and can be found in Appendix F.6. A list of operating assumptions for the proof of concept RSC*Model* model is also included in Appendix E.2.

4.5 Demonstration Feedback

As described in Chapter 3, a few demonstrations were made to the RSC*Model* team, sponsoring mangers, and managers at the partnering government organization at different points during the development of RSC*Model*. Some feedback was received by the RSC*Model* team from managers and practicing supply chain professionals following these various pilot contextual demonstrations. The feedback from these demonstrations provides the initial opinions, impressions, concerns, and recommendations from groups and individuals representing potential users and sponsoring organizations for further use and development of the tool. This feedback represents the primary empirical information available at this point in the project for making preliminary assessments of the tool. In all of the demonstrations thus far the tool has been well received and in general the feedback has been positive, with a few individuals providing specific feedback and suggestions.

One suggestion made during a demonstration of the tool to the sponsoring managers part way through the prototype development was for the inclusion of a pre-defined output graph showing demand versus production. The desire was to be able to easily see the relationship over time in order to identify gaps when production failed to meet the current level of demand. As a testament to the robustness of the RSC*Model* tool in gathering simulation data and easily creating customized reports for analysis, the development team was able to add this report during the demonstration immediately following the request. At the same time, some concern was also raised by sponsoring managers that the default output graphs currently provided by the tool look "cluttered," making it difficult to quickly identify important information.

Another concern raised during an onsite demonstration made to the partnering government "buyer" organization part way through the tool development process was that

RSC*Model* might be duplicating some capabilities that already exist in a typical ERP system. In response, the team prepared and sent a presentation explaining the key differences between a typical ERP system and a simulation based tool like RSC*Model*. The key difference is that ERP systems are basically in "transactional IT space," being concerned with simply acquiring, processing and communicating information at an operational level where simulation is an analytical tool used to make predictions and forecasts to solve problems and make decisions through realistic, dynamic representations of systems with uncertainty in inputs, constraints, and interdependencies. While newer ERP systems are offering more analysis based routines, they still do not offer the same level of predictive analytics that simulation tools offer.

A later demonstration and discussion with managers from the partnering government organization produced additional insights and suggestions. One individual participating in the demonstration was a manager concerned primarily with operations at the shop floor level with extensive knowledge about the sample part being represented in the sample supply chain in the model. This individual generally liked the tool but suggested that his greatest interest would be in using the model to analyze things like production start-up and demand variation in order to better understand the impact on schedule. The greatest value he saw coming out of the tool for someone in his position was the ability RSC*Model* has to provide output graphs showing why production is running behind schedule. He indicated interest in analysis capabilities for 'risk' primarily concerning the uncertainty surrounding bringing on a new supplier or producing a new part and the ability of suppliers to manufacture quality parts on a consistent basis, again with the primary value coming out of analysis of the effect on schedule. The ability to analyze the effect on schedule given "confidence levels of suppliers" that characterize their ability to manufacture parts was indicated as desirable. For the particular sample supply chain, there is a lot of prototype work done resulting in frequent production ramp-ups and small production runs. These production scenarios present unique challenges where suppliers are typically slow and ineffective in delivering parts at first. This prompted a request for more flexibility or customization to have more control over the actual production quantities that upstream suppliers can achieve over time in the model instead of just specifying a steady state demand for the entire simulation run.

This is valid and a good observation and recommendation, however, based on the functional specification RSC*Model* was made for analyzing steady-state production scenarios where such start-up issues have already been worked out. This was a conscious decision made during initial phases of the model creation to limit complexity in the proof-of-concept phase of RSC*Model*. RSC*Model*, at this phase was also not intended to look at "partial" supply disruptions as a form of risk, which are essentially what quality, yield, and other problems amount to. Despite this intended lack of functionality, based on this feedback and the desire to analyze issues with the production "ramp-up" phase of a new supply chain or supplier, one extra piece of functionality was added to RSC*Model* near the end of the prototype development. The option was added to define a weekly production capability profile for the first 30 weeks of the simulation for each part and supplier combination. This allows the user to define the percentage of baseline steady-state production for each part that the supplier is capable of which can be used to represent start-up conditions where yields are typically low and production is not yet optimized. He also expressed interest in the ability to experiment and see the effect on delivery dates with mean, max, and min delivery quantities from suppliers. This essentially is a request for the ability to perform sensitivity analysis as a way to identify what "risk" there is in the supply chain related to impact on performance in meeting the production schedule.

As part of the outputs following simulation runs he also wanted an easy way to determine what caused the schedule to slip to decide what action should be taken. This led to a recommendation that RSC*Model* include an improved event log for the simulation to see when critical events occur during the simulation. He did not focus on or seem as interested in the cost aspect of the tool, although he did note that the cost analysis in RSC*Model* could be helpful in make vs. buy decisions. He also indicated that program managers at a higher level would be more interested in costs. He suggested that program managers with responsibility for higher level assemblies with more supply chain related concerns would also find value in the tool and be more interested in costs.

The lead manager on the RSC*Model* project also presented the tool and findings at two conferences with manufacturing, supply chain, and simulation practitioners from the DoD and commercial enterprises in attendance. Managers from the sponsoring DoD organization for RSC*Model* were also in attendance. In the team briefing on the events, the RSC*Model* project manager and attending DoD representative indicated that the general audience reaction at the conferences was positive and that the demonstration of RSC*Model* was well received. A few individuals in attendance appeared to show some significant personal interest in plans for further development of RSC*Model*. While the general reaction to the basic approach and concepts of RSC*Model* were positive, a few comments and concerns were also brought up by various individuals. There were three specific suggestions reported from such feedback from potential users.

First, there was a request for a more "integrated" material cost solution. A high ranking official made this request, suggesting the need for a way to enter raw materials costs, such as for basic commodities, on a more global level within the RSC*Model* input sheets such that material prices for basic items could be input in a single location. It is easy to see how this could be helpful in analysis of much larger and more complex supply chains. If RSC*Model* is developed further to handle significantly larger supply chain networks this could greatly simplify and reduce the burden of data entry. The proof-of-concept tool can only currently model a fairly simple supply chain.

Second, another question arose surrounding the ability of RSC*Model* to query other databases for key information updates, such as Bloomberg for financial information that could be used to make inferences on the financial stability of supplier organizations. Essentially, the desire here seems to be the ability for the RSC*Model* tool to gather information from real-time databases to keep analysis current and to minimize the required effort for data gathering and input. RSC*Model* currently does not support any such linking to external databases. The potential power of such database links was not unrecognized during the development of the prototype tool. The functional specification for this proof-of-concept development effort purposely excluded such database links from the scope of work to reduce the complexity of the initial development effort. For risk analysis, such a capability to periodically assess the supply chain with up-to-date information would be very valuable. The other government funded tools that were evaluated for integration potential with RSC*Model* either already have or are pursuing such database links to improve their use. Whether it is best for RSC*Model* to incorporate such capability itself or link to another application aimed at identifying and assessing the likelihood and potential magnitude of risks remains in questions. RSC*Model* is currently focused primarily on assessing the impact, or long term consequences of risk events and how to best manage the supply chain to minimize those impacts and is not concerned directly with identifying the source of risk. Obtaining data for risk measures from other programs or databases would be advantageous. From a technical standpoint, RSC*Model* developers and team members did point out that such an enhancement to link to external databases should be feasible. In addition to native capabilities in ProModel, the use of Excel as the model interface allows great flexibility and power to make such modifications possible to interact directly with external databases.

A third request was the ability to maintain a database of supplier information. The suggestion here seems to be the ability to keep a database of supplier information that has been or could be used in future models and scenarios in RSC*Model*. Currently supplier information is simply created on a per model basis and the ability to keep a central database where supplier information could be stored and pulled from could greatly improve the ease of model creation and modification. Once such information is gathered and stored in a database it could also potentially be accessed and used with other programs.

The RSC*Model* project managers also participated in a meeting with a manager at the DoD's Defense Logistics Agency (DLA) to discuss RSC*Model*. The project manager reported that the meeting was "very productive" and that the DLA manager was very impressed with the ability to have a simple front end on a very complex software package. The manager indicated that this would allow him to make use of a broader group of casual users and could potentially lead to a change in his current strategy for modeling & simulation. Instead of using highly trained external consultants to run simulation software, a tool such as RSC*Model* could allow him to make use of such software at a new level and with new people. The DLA manager expressed further interest in the tool and indicated the desire for a complete live demonstration of the tool in the near future.

4.6 Effectiveness of RSC*Model*

Parts of the methodology that were executed, including the gathering of demonstration feedback, provide preliminary insights into the effectiveness of RSC*Model* in helping users make better decisions on how to manger supply disruption risks that ultimately result in lower Total Ownership Costs (TCO) of the supply chain.

4.6.1 Minimizing Supply Chain Total Cost of Ownership

As noted, this thesis explores effectiveness along three key dimensions, the first of which is the ability to minimize supply chain TCO. The limited ability to use the prototype tool in contextual experimental use cases with active supply chain practitioners severely limited the ability to gather definitive data on this factor.

The “buyer” survey described earlier shed some light on the current application and attitude toward this objective. One of the questions asked related to the importance of TCO in sourcing decisions and the factors used for its calculation. As mentioned, the response indicated a currently weak application of TCO in practice. The “buyer” was also asked, however, a question relating to how valuable it would be if the supply chain could be designed upfront to minimize TCO. The recorded response was simply, “Important.” In the case of the specific sample supply chain, the objective to minimize TCO is seen as important and not well implemented. This provides an opportunity for a tool like RSC*Model* to deliver desired capabilities. In addition, the literature review provides support for the proactive formulation of risk mitigation strategies possible with RSC*Model* as generally more costs effective than post-disruption recovery efforts.

The actual ability of RSC*Model* to provide more useful information to manage supply disruption risk in a way that minimizes TCO, however, is still in question. Unfortunately, little to no empirical information was obtained. Feedback from demonstrations indicated that such capability would be found useful by supply chain practitioners, but without hands-on experience, it is difficult for even experience supply chain professionals to assess the usefulness of a new tool in helping reduce costs. From a theoretical standpoint, the concept appears to be sound and desirable. Personal investigation of the tool however reveals that the execution of this capability is still lacking. The tool provides a pre-defined output graph showing TCO by supplier and by supply chain. As these are only two basic cost types that can be entered in the model, the calculation of TCO for the supply chain in the current model is made up primarily of the defined unit prices for components throughout the supply chain from each supplier, including base costs and any adjustments for higher or lower than normal production quantities, and any related "business" costs incurred over time throughout the simulation run. This limited functionality is limiting and appears to be insufficient for an effective use of TCO, and for any user of the tool, the costs included in the calculation are not entirely clear.

The RSC*Model* tool needs to more clearly define which costs are included in the calculation of TCO and what data is needed to make those calculations. Ultimately, determining which costs to include in a supply chain TCO calculation is a matter that needs further research and investigation. It is also unclear where "cost" values are used and where "price" values are used to allocate cost to TCO which ultimately makes a difference in how TCO would be calculated. For example, it is not clear whether monetary values for various components are based on unit "prices" indicating the value paid by the downstream supplier, or simply the new "costs" the supplier incurred in performing its operations without the inclusion of profit margins.

It is apparent, however, that improved cost application and measurement is needed for different cost drivers that are both direct and indirect, and both incurred (actual monetary) and non-incurred (non-cash payment) costs. Ultimately, to provide an effective TCO calculation for identifying the impact of disruption risk and mitigation strategies this would likely include costs related to carrying inventory (storage, warehousing, obsolescence, etc.), transportation, contractual penalties, lost sales, supplier retainer capacity, changes to volume discounts, supplier quality costs, and many others. It appears that RSC*Model* currently does not track enough of these type cost to get a robust picture of the TCO of various disruption risks and risk mitigation strategies. Some of the types of costs mentioned could very well be included in the model through the purchase price and "business" costs that can be defined on a one time, per unit, or by PO basis although this is not a direct and straight-forward approach for inexperienced users. An initial cost required to bring on a replacement supplier, for example, could be included as a one-time business cost and a higher piece price could be included to represent higher transportation costs from a new supplier, etc. Various costs therefore can be represented, the method of representation, however, is not very explicit.

4.6.2 Ease of Learning & Use

Like minimizing TCO, the evaluation of ease of use and learning was also severely limited due to the lack of hands-on use and review. Despite the lack of feedback from personal, hands-on use by supply chain professionals, based on demonstration feedback there appeared to be no major complaints about the approach of using Excel as the user interface to both enter data and to automatically provide the means to create a simulation model and provide a visual representation of the supply chain network. This approach provides a flexible framework that is reusable making it possible to easily model various supply chain network configurations simply by entering data. A very positive indication about the perceived ease of use and learning of the tool came out of feedback from one demonstration. As described, one individual with managerial authority over modeling and simulation use and strategy in one organization liked the approach and indicated that such a straightforward approach to modeling provided by the tool could allow a major shift in strategy for modeling and simulation based analysis by allowing other decision makers with less modeling experience to use the tool. One noted limitation of typical simulation based analysis approaches noted in the literature review is that of typically low stakeholder involvement due to long lead times for model creation and analysis, and that models are often built and used by persons not responsible for the decisions driven by the analysis. With the simple user interface, as mentioned, RSC*Model* can help overcome these obstacles by bringing the use and analysis closer to the decision makers. This could additionally make the tool more accessible and useful for risk management using cross-functional teams which are generally seen as important for effective risk management.

As mentioned, the form of some data types required by the model should be familiar to the target user group; namely, the use of Purchase Order tables to define the demand signals and Bill of Materials to define the subcomponent hierarchy. These familiar data types should increase ease of use and make it easier to learn and understand what is happening in the model. RSC*Model* also provides an easy way to define disruption risks in the supply chain using terms and elements (probability and duration) that are easily understood. The ability to mix and match different datasets for suppliers, BOM, Costs, PO's, etc. provides flexibility in scenario design, potentially improving ease of use. As far as gathering that data goes, however, RSC*Model* has a disadvantage that relates to ease of use. Specifically for disruption risk identification and quantification, RSC*Model* provides no means to find the values needed for the model. The same relates to other data elements and as noted in the review of the buyer and supplier survey procedures and results, it can be seen that a manual data gathering process can be difficult and time consuming.

Simulation models can also quickly become complex, and supply chain models are certainly no exception as they have many different elements, rules, and interdependencies that only increase as the size of the supply chain to be modeled increases. It can be easy, then, to make a mistake in building a supply chain model that renders it invalid and unusable, and the larger the model is the harder it can be to identify the mistake. The ability to mix and match datasets, while potentially making it easier to build scenarios may increase the potential to build models with incomplete or incompatible data. Automated model verification methods that check to ensure supply chain models will actually work and help pinpoint errors become important. RSC*Model* was built with some error detection functionality but it is limited in this prototype phase and without a robust hands-on evaluation procedure it is difficult to determine the true usefulness of the method.

As mentioned, Excel does provide a familiar front-end to a simulation tool that would be difficult to understand for someone without any simulation modeling experience. The use of Excel should provide a familiar and user-friendly interface for data input and model operation as it is the industry standard spreadsheet application. While the use of Excel as the user interface works for this prototype model, it does appear to present some limitations for future expansion and scalability of the tool. A general observation by the author is that expansion of RSC*Model* to handle very large complex models may become somewhat “clumsy” in Excel, requiring lots of scrolling and a limited ability to provide easily understood visual representations of the model that can be manipulated graphically. As the tool is further developed to handle larger models the use of a database for data may be a better option moving forward. Whatever interface is used, the option for a more scalable solution for representing various sized supply chains with the ability for the user to create more "nodes" in various configurations without the need to change hard-coded elements of the input templates would presumably increase ease of use in a wide variety of tool applications.

A generally observed and widely known issue that is worth repeating here is that any new software application that is intended for use in a military computing environment will face a lengthy review process before implementation and use of the tool can begin. Much of this is for obvious security reasons for new software and technologies, but in any case the initial effort required to use such a tool can be substantial and this project proved to be no exception.

4.6.3 RSC*Model* Integration Opportunities

An important piece of the RSC*Model* development process was the evaluation of various other government funded supply chain risk analysis tools (RANGER, PrimeMap, and PrimeSupplier) as described and reviewed in Chapter 2. A significant part of this analysis was the assessment for integration potential among these tools and RSC*Model*. The prepared diagrams mapping the basic inputs and outputs of the tools and the conceptual integration diagrams (Appendix F) preliminarily indicate that RSC*Model*'s capabilities could contribute and play an important and missing role in an overall suite of tools for risk management. On the same note, the diagrams indicate that RSC*Model* could help fill in a gap in the risk management process and does not replace the capabilities of some other tools. The diagrams also show how RSC*Model* is missing capabilities for much of the important up-front steps of the risk management cycle but provides an important final piece that other tools are lacking, this primarily being the simulation and evaluation of impacts and strategies for dealing with disruption risk.

While each of the product sets described has a different focus and approach to assessing and mitigating supply chain risk, they were all found to complement each other in ways that could be used to produce a synergistic solution. For example, one possible integration scenario identified is for PrimeSupplier and PrimeMap to feed RANGER various risk probabilities based on real world information. RANGER could then use this data to calculate resultant risk probabilities that can then be feed to RSC*Model*. Additionally, the Prime products could directly feed risk severity information to RSC*Model*. RSC*Model* could then perform a dynamic assessment of alternative risk management strategies using discrete-event simulation. The RSC*Model* recommendations could then ultimately be fed back into RANGER or the Prime tools to do further probability reduction studies. The Prime tools further provide supplier health information that can be fed into RSC*Model* to assess the agility of the supply chain.

Ultimately, however, the analysis provides only a preliminary, conceptual analysis of such integration potential. As stated, the technical feasibility, effort, and other considerations required to make such integration a reality were not explored in depth. RSC*Model* currently does not interface with any other programs or databases although ProModel and Excel both have a diverse set of user interface options that would enable data to be exchanged with other applications and supply chain analysis tools. The conceptual integration diagrams did, nonetheless, receive a warm reception when reviewed by the project managers for the other products, with one wanting to share them internally with colleagues. The diagrams were also well received by a high ranking official overseeing the RSC*Model* project. This individual requested the further preparation of a concise version of the diagrams to include in presentations demonstrating and promoting RSC*Model*. The condensed integration diagram is included in Appendix F.8.

4.6.4 Theoretical Evaluation of RSC*Model* – Additional Considerations

Based on the principles and findings on disruption risk management from the literature review, a general assessment of the RSC*Model* tool is provided here. This assessment acts to augment the findings from feedback received from the pilot contextual demonstrations, and highlights strengths of the tool as well as areas in need of further development or investigation for further development of the tool.

As with the other risk tools reviewed, the relevance of the capabilities and method offered by RSC*Model* for each of the four basic risk management process steps is assessed. As far as relevance for each step goes, RSC*Model* is very similar to the other simulation based tools. Simulation based tools in general tend to offer some capability to identify potential for disruptions in a supply chain since they can accurately replicate the dynamic nature of supply chain activities. The prototype RSC*Model* tool, however, seems slightly less capable of helping to identify risks at this stage of development for two primary reasons. First, the modeling in RSC*Model* is only focused on representing individual supplier nodes keeping the simulation at a high level that does not allow for a wide variety of potential constraints or other issues to be examined that may occur due to lower level details in a supply chain. Second, the currently permitted inputs for RSC*Model* do not allow for stochastic modeling of most processes in the supply chain. Disruption risks are defined with variation by selecting a probability of occurrence over a specified time period, but other model elements such as supplier production rates are not currently defined with any variation in the model. Similarly, this limits the ability to identify potential disruptions that may occur due to natural variations in the system. Similar to other simulation tools, RSC*Model*'s strength is in providing a method to assess the impact of supply disruption risk and to create and test various management strategies to find the best way to mitigate disruption risks. Like other simulation tools, RSC*Model* also offers some potential to monitor disruption risk and implemented management strategies by using the tool to simulation and evaluate a representation of the current state of the supply chain. A perceived benefit of RSC*Model* as a simulation based "predictive" analytic tool, however, is that the risk monitoring step plays less of a role in the risk management process than in traditional trial-and-error or Plan-Do-Check-Act type approaches. The perceived relevance of RSC*Model* for the process is shown in Figure 4.6.

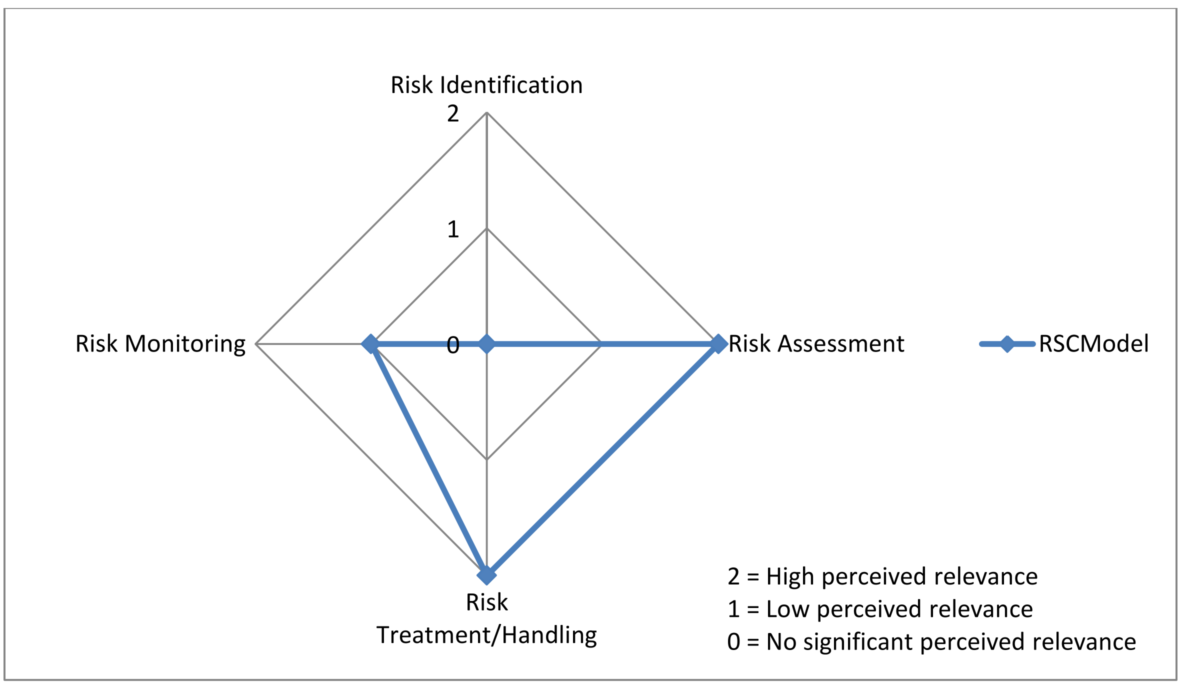

Figure 4.6 – Perceived relevance of RSC*Model*

As described in Chapter 2, any analysis of risk needs a specific definition and way to view risk. RSC*Model* is fairly clear that it is looking at supplier disruption risk, although as described, this focus is easily extended more generally to "supply" risk that is concerned with the possibility of any disruption in the flow of goods in the supply chain that originates from a supplier or transportation from that supplier no matter what the root cause. The proposed view of risk presented at the beginning of this chapter helps define how RSC*Model* views risk and helps understand where RSC*Model* has potential to contribute most to the risk management process. This three part view of risk is used by RSC*Model* in assessing supply disruption risk. Based on the proposed view of risk, there are three parts to supply disruption risk: the probability that a disruption of a supplier (or its ability to transport or deliver goods) occur, the magnitude of the disruption, and the resulting impact on the supply chain performance. For the current prototype RSC*Model* tool it is expected that the probability and magnitude of expected disruptions are determined outside of RSC*Model* and the values are simply accepted as given in the model. This focuses RSC*Model* on the assessment of impact (Figure 4.7) which is appropriately separated in the model from the magnitude of the risk. Part of clearly defining risk is also described in Chapter 2 to be concerned with determining exactly what factors will make up the assessment of risk "consequences" or impact. RSC*Model* is clearly focused on supply disruption risk and the impact on cost, however, as described in the discussion on minimizing TCO, determining exactly what cost impacts will be used in TCO is one area where RSC*Model* seems to be lacking. RSC*Model* needs to better identify what factors it is going to look at to determine impact on TCO. As seen from the feedback gathered, some potential users may be interested in some measures of impact more than others. Determining the target audience for the tool helps determine what it should measure.

Related to the limitations of TCO in the current RSC*Model* tool is that it really only evaluates one side of the classic cost/service trade-off for supply chains. It does not currently address the issue of identifying the right service level to give the lowest cost or how that trade-off is affected by supply disruption risks. Instead, RSC*Model* has made a simplify assumption about the trade-off by simply making the goal to be a 100% service level.

Probability	Magnitude	Impact
Potential or likelihood of occurrence of risk event within some time frame • *What is the likelihood the risk event will happen?* • *Where is it likely to happen?* • *When is it likely to happen?*	Magnitude of risk event (degree and duration) • *How long will the disruption last?* • *Who/What (which suppliers, what parts) will be affected?*	Loss or undesirable outcome on performance from extended consequence of risk event • *Δ Total Cost of Ownership (TCO)* • *Δ Service level*
		RSCModel

Figure 4.7 – The focus of RSC*Model* in proposed view of supply chain risk

As described by the chart in Figure 4.7 and the fact that RSC*Model* simply accepts the probability and magnitude of disruption risk, RSC*Model* does not offer a full supply chain risk management solution. Ultimately, RSC*Model* requires another tool(s) or information source(s) to determine the probability and magnitude values to define the risk. Without current functionality built in to link to other tools or data sources for risks, the ultimate potential of RSC*Model* is not yet realized since data gathering and entry can be a tedious process that inhibits usability and therefore the effectiveness of the tool.

RSC*Model*'s contribution to risk management, then, is primarily limited to reducing, or mitigating, the impact of a risk event since it does not explicitly provide the means to look at or evaluate management strategies that could reduce the probability or magnitude of the risk. In other words, RSC*Model* does not provide the means to view risks in the causal chain fashion presented by Fenton and Neil (2006b) to understand root causes (triggers) or develop and evaluate "controls" that affect the probability or magnitude of a risk event. For example, the source of a supplier disruption may be an earthquake which causes damage to a supplier facility.

As described RSC*Model* simply takes the resulting length of disruption as a given and does not consider what controls measures could be taken to reduce the length of the duration, such as infrastructure changes, etc., and what the cost of such options might be. Even though it does not explicitly look at these options, RSC*Model* could again be used in a “sensitivity analysis” type fashion to see the effect on TCO if it were possible to reduce the probability or magnitude of a risk event by some amount. In this way RSC*Model* could be used not only to determine what the lowest TCO is that can be achieved through management strategies given a certain level of risk but also what level of risk is possible while still not exceeding a target TCO. A robust implementation of TCO measurement in RSC*Model* would provide important information used in a cost-benefit analysis for risk control measures.

The ability to predict the impact of disruption risk also has importance and value in its own right. A difficulty in risk management is knowing which risks pose the biggest threat to performance and which should be addressed first. Simply knowing the probability and potential magnitude of a risk is not sufficient. Without knowing the impact it is difficult to prioritize mitigation efforts. The concept of RSC*Model* is to help show what the real cost of the risk is so better risk management decision can be made. Once data is available, RSC*Model* can help predict the impact and then to understand what the best options are to mitigate the risk so that the most cost effective risk management projects can be put in place first. Ultimately, this provides a key capability ("Best Practices for Supply Chain Improvement" 2011; Proctor and Smith 2010) in helping link high level strategic decisions with lower-level operational decisions.

Additionally, even without the capabilities to provide a systematic method to identify possible supply disruptions and to quantify the probability and magnitude values for the risk, RSC*Model* still provides a key capability. Based on the discussion of Black Swan type events, it is not always possible to identify all disruption risks and efforts to quantify the risk may be fruitless or impractical. RSC*Model* has the potential to be an effective sensitivity analysis tool to test a supply chain for resiliency to any imaginable disruption risk. This could be used as well to identify where the largest vulnerabilities lie in the supply chain in terms of potential impact. RSC*Model* then not only provides important capabilities for developing pre-disruption mitigation strategies and resilient supply chain design, it could also be used to develop contingency plans that could be put in place in the event that a disruption event actually does occur. Similarly, RSC*Model* could also be used to help make cost-effective management decisions about supply disruptions that are not technically risks at all because the issue is already a known problem.

As mentioned, the probability of a supplier being disrupted over a specified time period is the only real stochastic element in current models and scenarios created with RSC*Model*. While this kept the model simple for the proof-of-concept development it does present limitations in use. There may also be uncertainty about the likelihood of a disruption occurring within a given time period, when in that time period a disruption may occur and the duration of the disruption. The option to represent the probability and the magnitude of disruption with a probability distribution could provide a more appropriate way to define the uncertainty about the risk. The ability to include variation in other model elements, as described, would enhance the ability to more closely represent the supply chain.

Another current limitation of RSC*Model* related to the lack of methods to identify and quantify risks and ultimately the ability to provide the information needed to reduce TCO, involves understanding newly realized supply chain risks. Form the discussion of risk in Chapter 2, part of risk management involves understanding what different or new risks might be present or result from efforts to mitigate risks. Changes made the supply chain network, such as bringing on a new supplier for example, also involve a level of supply disruption risk, and to truly understand the effectiveness of risk mitigation strategies in terms of TCO these risks would also need to be taken into account. RSC*Model* does offer the potential to define disruption risks for replacement suppliers, but again, it does not provide the means to identify the new risks or quantify the probability or magnitude of those risks. This leads to the chance that there may be a false assumption in RSC*Model* when redesigning a supply chain that supply disruption risks will stay the same under a new configuration. For example, a new multi-sourcing strategy for a component may give current suppliers less business and therefore put them at a higher risk of financial troubles that could result in a supply disruption. RSC*Model* does not offer the means to monitor and determine this change in risk.

As described, limited supply chain visibility is a challenge making supply chain risk management difficult in many supply chains. RSC*Model*, like many other modeling tools, provides a catalyst to increase the visibility in supply chains since detailed data about the supply chain network must be gathered to use the tool. In addition RSC*Model* offers a visual representation of the supply chain network relationships through minimal effort on the part of the user which improves visibility. It does not, however, currently provide any information technology related tools or methods to gather supply chain data or to track and monitor current data.

4.6.5 Comparison with Other Tools and Methods

A main part of the hypothesis of this thesis is focused on the effectiveness of RSC*Model* compared to other current tools and methods "in providing the information necessary to make supply chain risk management decisions that minimize total cost of ownership of the supply chain." A review of a set of various other tools and approaches has already been provided in previous sections. A brief overview of some key points of comparison between the various tools reviewed and RSC*Model* is provided here.

Diagrams showing the perceived relevance of different tools for the four steps in the basic risk management process have been provided. Figure 4.8 combines these into one diagram. While the review of tools for this thesis did not include all currently available tools, even from this small sample it appears that various tools offer different strengths and that no one tool is likely to provide all the information, capabilities, and functionality needed for effective execution of every step in the risk management process. In terms of relevance for these steps, RSC*Model* is similar, as mentioned, to other simulation based tools reviewed and lacks capabilities for risk identification and monitoring as well as part of the risk management process. In order to provide a holistic approach to manage supply disruption risk in a supply chain a complementary set of risk management tools is ultimately needed. The potential for synergies among some of these tools has already been explored in previous sections.

Beyond addressing each of the steps in the basic risk management process, different tools have different sets of capabilities to address each step, some providing more effective methods than others. One area where RSC*Model* is currently lacking compared to some other tools is in efficient experimental planning. Tools like Supply Chain Guru (SCG) provide various optimization routines for different aspects of supply chain design that could help guide initial formulation of strategies that will reduce TCO of the supply chain. RSC*Model* and other tools appear to be lacking here, although, SCOR based tools do provide best practices for supply chain design that could also be useful. Another key method to improve risk management strategy formulation is the ability to do multi-scenario analysis. RSC*Model* and other simulation tools like SCG allow this as well.

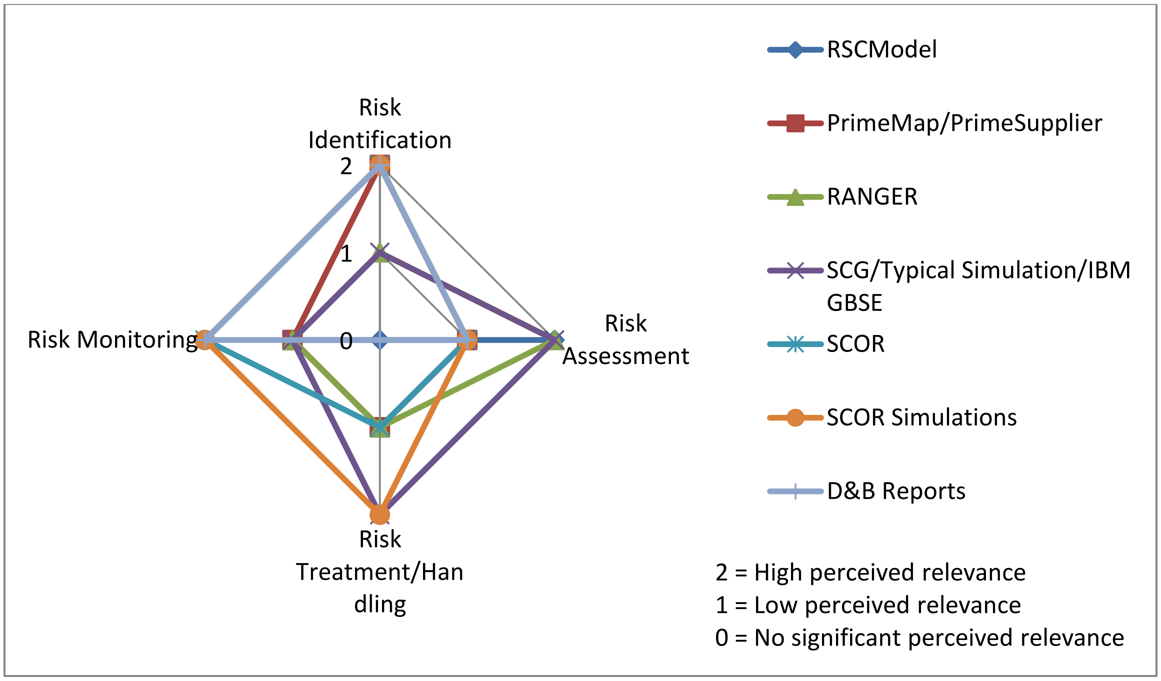

Figure 4.8 – Perceived relevance of all reviewed tools

None of the other tools reviewed for this thesis focused exclusively on analyzing supply disruption risk in supply chains as RSC*Model* does. The other simulation based tools reviewed are primarily more general purpose supply chain analysis tools which also provide some methods for risk analysis. From information available it is also not clear how the tools specifically address disruption risk or even risk in general. SCG allows users to "introduce disruptive events," but it is unclear exactly how they are introduced or what type of data is required. The focus of RSC*Model* on minimization of TCO does appear unique, although comparatively, its cost assignment and tracking abilities in models do not appear as developed and extensive as other tools. Also related to cost, the 100% service level goal of RSC*Model* simplifies supply chain management decisions, however, other tools such as SCG provide methods to perform optimizations and analyses, such as inventory optimization, while taking service targets into consideration.

As described in a previous section, a major characteristic of RSC*Model* that makes it easy to use is the use of Excel for data input and creation and running of the model. The review of other tools reveals that this is not an entirely unique approach. Many standard simulation programs and even some non-simulation based tools allow for use of Excel as a data entry mechanism. The use of Excel to build the model based simply on user defined data and to visually represent the supply chain does not appear to be common; however, other tools provide other user-friendly methods for model and scenario creation including visual drag-and-drop type approaches. Also, some other tools such as SCG have automatic data connections to external databases which can make modeling of the supply chain much quicker and easier than methods and tools that require manual collection and entry of data as RSC*Model* currently does. RSC*Model* does provide technical elements that should make such connections fairly simple in the future. Some of the other data input approaches such as using familiar BOM and PO data formats used in RSC*Model* improve ease of use but are found to not be entirely unique. IBM GBSE, for example, also uses a BOM approach for data input. Additionally, even though tools like RSC*Model* can make model building easier by automatically creating models from data without having to design special logic, they can still be complicated in that the user must understand what the assumptions and conventions are used in the model. SCOR type models that are based on already widely accepted and understood processes provide an advantage in modeling assumptions being potentially more easily and quickly understood.

One of the challenges described in the literature for use of simulation methods for analysis of supply chains was determining the appropriate level of detail for the model and supporting different levels of detail for different areas of the model. RSC*Model* currently sticks to focusing on one level which serves its current approach and focus well and keeps the model simple and consistent. It does not provide any easy method to model more detailed supply chain elements than simple supplier nodes in the network. RSC*Model* does allow for some more detailed modeling of business policies for costs, inventory, timing of production, etc., but in general the ability to alter model details is not as robust as some other tools. SCG, SCOR based models, IBM GBSE, and typical discrete-event simulation tools and models provide more flexibility in terms of the level of detail for supply chains that can be modeled. This includes the ability to model details related to disruption risk such as transportation as well as specific facility processes and resources or assets. The increased detail possible could permit more visibility and therefore more disruption risk identification and impact analysis at a lower, more tactical level. Some tools however, don't allow the flexibility that RSC*Model* offers in making modifications. The options to modify models and to view network models visually in realistic geographic representations and to filter views are also more robust in SCG. These types of details become more important as the scale of supply chains modeled gets larger.

In addition to some other tools offering more stochastic modeling abilities, presumably through the simple user interfaces, some tools offer analysis with seasonality of demand and product life cycles. RSC*Model* has been purposely focused on steady-state production for the prototype, however this is another area where RSC*Model* could expand functionality in the future for more realistic supply chain representations. Some tools, such as SCG, improve ease of access through web-based versions of analysis tools. This is something RSC*Model* currently does not provide, but is an important capability that has the potential to make it easier to get the needed information into the hands of various decision makers. Even still, RSC*Model* does provide a simple means to model and simulate risk and put it in terms that business decision makers can understand, which is, on its own, an important step in getting useful information into the hands of those that need it most for making important decisions about risk.

Of all the tools reviewed, SCG appears most comparable to RSC*Model* in terms of capabilities and functionality, offering ways to perform much of the same analysis possible in RSC*Model* with some additional capabilities that could improve the process further. Without hands-on use of the tools by the target audience of supply chain and program managers it is difficult to make definitive assessments about the capability of one to provide a more effective means to obtain the information needed to minimize the Total Cost of Ownership of a supply chain.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The unfortunate lack of quantitative data generated for this thesis has made it difficult to draw definitive conclusions about various parts of the research methodology and ultimately the hypothesis. As such, this thesis has relied heavily on qualitative analysis and information from literature review to guide evaluation of RSC*Model*, the new and collaboratively developed tool for managing supply disruption risk prevalent in modern supply chains. A comparative analysis to other current tools and methods reviewed in the literature also plays a fundamental role. Since RSC*Model* is the result of a pilot development project creating a proof-of-concept and prototype tool concurrently with this evaluation effort, this thesis has also provided an exploratory study for understanding and viewing supply disruption risk and effective ways to manage the risk in modern supply chains. Feedback from supply chain practitioners participating in pilot contextual demonstrations also provided some valuable, although limited, qualitative information on the perceived effectiveness of RSC*Model*.

Ultimately, with limited empirical data and a prototype and proof-of-concept tool that still lacks robust functionality and execution of design concepts, this preliminary study fails to reject the null hypothesis that "RSC*Model* is no more effective than current tools and methods in providing the information necessary to make supply chain risk management decisions that minimize total cost of ownership of the supply chain."

RSC*Model* is currently a tool that holds lots of promise as an effective tool for managing supply disruption risk in supply chains with a sound approach to improve the assessment of risk impact and subsequently the development of cost-effective risk treatment and handling approaches for risk management. Like most risk management tools, it fails to provide a holistic solution for all steps of the basic risk management process. Like most simulation-based tools, RSC*Model* relies on and could greatly benefit from the capabilities of other risk related tools for risk identification and assessment. However, even within its area of focus, as a prototype tool it still lacks the robustness and full range of supply chain management capabilities of some other current tools. While RSC*Model* demonstrates the feasibility of creating a tool that addresses the various shortcomings of current management techniques explored in this thesis, it currently still lacks the full range of capabilities and functionality to unequivocally be considered as more effective in providing information for effective disruption risk management and minimization of supply chain TCO related to supply disruption risk.

The comparative analysis of other tools demonstrates that most of the primary capabilities and elements of design that permit ease of model creation and use may in fact already be available. This certainly does not mean that RSC*Model* provides no effective concepts for improving management of supply chain for supply disruption risks. Even though they may provide such functionality, other available tools do not promote or focus on risk management from a total cost perspective. The view of risk and method for analysis provided by RSC*Model* also appears unique and theoretically appears viable for making risk management decisions that decrease total supply chain costs. The feedback received from supply chain practitioners following pilot contextual demonstrations reveals a general positive attitude and interest in RSC*Model*'s approach. Unfortunately, this information is primarily anecdotal and a more structured and scientific evaluation approach needs to be executed to better address the hypothesis of this thesis. The preliminary design for such an evaluation has been provided in this thesis. Further development of RSC*Model* capabilities to functionalize design concepts is likely needed before an effective and worthwhile execution of such a study can occur.

5.2 Recommendations for Further Tool Development

The review and comparison of other current tools and approaches for risk management in supply chains revealed several areas where the functional specification of RSC*Model* could use to be expanded to improve effectiveness of the tool. Understandably, RSC*Model* lacks various capabilities and functionality in its current prototype state. To reach its full potential and be practical and useful in industry for management of supply disruption risk, however, it needs further development for many of the important additional features identified and explored here.

5.2.1 Improving Functionality

A few specific enhancements necessary for improving the functionality of RSC*Model* are identified and discussed here:

- Improved cost measurement and allocation for TCO
- Add or integrate capabilities to identify and quantify supply disruption risks
- Expand supply chain modeling capabilities including more stochastic elements

The primary concern for enhancement of RSC*Model* is the use of TCO in the tool. As an objective function of the tool, minimization of TCO needs to be supported by more robust and extensive measurement of various costs. Determining exactly which costs should be included in the TCO calculation for analysis of supply disruption risk is an area that needs further study. As described a study of risk needs to involve identification of which factors, in this case costs, will be considered in evaluating the impact. It needs to be better defined and then included in the model which consequences of disruption risk will be assessed and then how the costs associated with those risks will be tracked and measured. As part of this, RSC*Model* also needs to take a broader look at the effect of disruption on service levels and how that relates to TCO. RSC*Model* must also make a specific and consistent distinction on what "cost" and/or "price" values are used in the model and how they are applied in a valid manner to TCO calculations. Adding up component purchase prices up and down the supply chain, for example, will not provide a valid picture of total cost in the supply chain.

In order to provide a more holistic approach to the management of disruption risk in supply chains, RSC*Model* needs to either add capabilities to identify risks and quantify risk probabilities and magnitudes, or, identify other information sources and develop technical capabilities to allow for RSC*Model* to be fed or extract data from those sources. This will also help identify risks related to any proposed network changes for new management strategies which will improve assessment of TCO. A few potential tools and data sources have been identified and suggested in this thesis. In addition to providing background information on appropriate ways to identify and quantify risks, this thesis also has provided useful information to help guide effective processes for managing the root causes of risk and reducing the probability of risk, which RSC*Model* currently does not address.

Modification of the tool to allow for more robust and realistic models of supply chains should also improve risk management decisions. Some of these modifications include allowing easy creation of more stochastic model elements for production rates and other process factors, as well as for defining the probability and magnitude of disruption risks to be analyzed. Methods to represent seasonality in demand and disruptions as well as product life cycle stages would also add a new useful dimension to the analysis possible with RSC*Model*. A more direct focus on logistics links in supply chain networks and the potential disruption risks they contain is another piece of functionality that would enhance risk analysis and formulation of risk management strategies in the future.

5.2.2 Improving Ease of Use

A few recommendations for improving ease of use of RSC*Model* are to:

- Identify and link data sources for supply chain network design
- Explore a more dynamic and scalable method for defining the supply chain network
- Utilize a web-based implementation of the tool

Data gathering and data input methods that create the model and drive model behavior should be enhanced to provide more automated processes to speed up model creation. As RSC*Model* is expanded to support analysis of larger, more complex supply chain networks, this will become increasingly important.

The use of Excel as the interface for data input, model creation, and simulation provides several identified benefits. The current implementation is somewhat limiting for expansion to support large scale supply chain models. The possibility of further expansion also requires the expertise of the tool developer. A more dynamic method to allow larger model definition with more suppliers in a similarly easy way could greatly enhance ease of use.

A potentially major advantage in ease of use of a competitive, simulation based risk modeling and analysis tool is the availability of a web-based version of the tool that allows easy access and sharing of analysis and models within and across organizations in the supply chain. This provides the potential for effective use of cross functional teams of risk management decision makers.

5.2.3 Improving Reports

A couple recommendations for improving the reports provided by RSC*Model* are to:

- Identify and display only a set of key output reports, with easy access additional reports
- Provide key performance metric values as outputs in addition to time plots

A suggestion made by a manager from the sponsoring government organization was to reduce the cluttered look of predefined output graphs provided by the tool. This may potentially require that fewer graphs be shown by default and only the most important graphs related to key performance metrics be shown immediately following the simulation run. These would include basic total cost and service level related graphs. In addition to the time plot graphs provided, the reporting of individual key performance metric values would provide for easier preliminary comparison of different simulation scenarios.

5.3 Suggestions for Future Research of RSC*Model*

Providing preliminary research and background information on current knowledge and views about management of disruption risks, this thesis provides a great “jumping off” point for future research to expand on the core concepts of RSC*Model*. As RSC*Model* is developed further, more structured evaluations of its effectiveness compared to other approaches should be conducted. Further research is needed to help guide future expansion of tool functionality as well.

5.3.1 Future Evaluations of RSC*Model*

The proposed evaluation procedure and surveys designed for this thesis serve as a guide and starting point for a more thorough and empirical assessment of RSC*Model* and its ability to address the hypothesis of this thesis. A key part of future evaluations should be the inclusion of actual supply chain practitioners who use RSC*Model* in a structured evaluation procedure. A more "hands-on" assessment of the tool by actual target users is the next important step in generating actionable feedback to guide further tool development. It would be advantageous in this evaluation procedure to allow potential users to perform risk analysis and develop risk mitigation strategies using a variety of currently used tools in the market, such as Supply Chain Guru. This would allow for more robust and reliable comparisons among current risk management tools and approaches.

5.3.2 Other Research Questions to Address

Based on the research presented in this thesis, there are several important research questions to be addressed to further guide the design concept of RSC*Model*. Some of the most pressing questions are as follows:

- Is minimizing TCO always the single most important goal for risk management?
- What are the potential side-effects/unintended and undesirable consequences of only focusing on minimizing TCO of a supply chain?

- Is there a universal set of cost drivers that a model can include and track that is appropriate for analysis of any supply chain? Or, do TCO calculations always have to be tailored to specific supply chains?
- When is it better to take a contingency plan approach rather than a more proactive supply chain network design approach for mitigation of risk?
- Can a tool be developed that can both help identify and predict risks as well as analyze impacts and guide appropriate mitigation strategy development?

Additionally, there are several topics and areas of research to explore. This research provided a review and comparison of a small sample of risk management tools. A broader search, identification, and review of other tools would enhance the understanding of current practices and gaps in available offerings. Further, this study should include a closer examination of which tools are actually used in practice in industry and how and why they are being used. Similarly, tools that are available and present viable methods to enhance risk management but are not being used should be explored to determine drawbacks that are limiting their implementation. The synergistic relationship between RSC*Model* and other tools, specifically the government funded tools reviewed for this thesis, needs to be further explored to fully leverage past and future investments in tool development and enhance the effectiveness of RSC*Model* by providing capabilities that RSC*Model* lacks in the overall risk management process. Necessary technical requirements to make such integration and data sharing possible and practical need to be determined. These requirements are needed to help guide future development efforts of the different tools.

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APPENDIX A PROPOSED EVALUATION METHOD

A.1 RSC*Model* Evaluation Proposal

Date: 30 May 2011 *(Revised 31 October 2011 for inclusion in thesis)*
Authors: B.J. Saunders, Charley Harrell

Proposal for Evaluating the Effectiveness of RSC*Model* (Draft)

INTRODUCTION

This proposal outlines a procedure and corresponding requirements for evaluating the effectiveness of RSC*Model* in terms of both ease of use and improvement in the quality of agility and risk mitigation decisions that are made. This evaluation plan involves the design of a range of test case scenarios based on the *sample part and supply chain used in* RSC*Model development or a similar generic sample supply chain network*. After conducting a set of experiments based on these scenarios in which a PM makes supply chain planning decisions with and without the use of RSC*Model*, a comparison of the decision quality will be made. The difficulty a PM has in learning and using RSC*Model* will also be assessed.

PROPOSED APPROACH

PMs, or other supply chain "experts," are provided with a "realistic" baseline supply chain (based on *sample part and supply chain used in* RSC*Model development*) and two disruption and two surge/sag scenarios. The PM will be asked to verify whether these scenarios are representative of what a PM might expect to encounter in actual practice. The two surge/sag scenarios include: (1) a six-week surge in demand that exceeds the most constrained supplier surge capacity by ten percent and (2) a six-week sag in demand that equals the most constrained sag capacity (any lower than this would create a supplier disruption scenario). The two disruption scenarios include: (1) a temporary supplier failure lasting six weeks and (2) a permanent supplier failure. PMs are asked to determine the most cost-effective way to manage these scenarios in three phases: (1) independent of RSC*Model* management parameters, (2) without RSC*Model* but within parameters, and (3) with RSC*Model*. RSC*Model*'s optimization capability is also used to develop a solution independent of the PM. The effectiveness of

RSC*Model* is then evaluated through comparison of developed surge/sag or risk management strategies and with feedback in the form of expert opinion and data gathered from the PMs through surveys and interviews. Effectiveness of RSC*Model* is measured along three key dimensions:

1. Ability to minimize supply chain total cost of ownership
2. Ease of use
3. Ease of learning

The scenarios developed for these test cases could be leveraged in the future for demonstration purposes to promote the use of the tool.

NEEDS AND REQUIREMENTS

- *Sample supply chain used in* RSC*Model development* configuration and operational data for complete scenario development and subsequent internal evaluation and testing.
- Participation and cooperation of 3 program managers (or similar supply chain "experts") willing to participate in the evaluation process and provide feedback in a timely manner.
- RSC*Model* user instructions and remote or on-site resources provided for administration of test case to PM and collection of data through surveys and/or interviews.

FORM OF RESULTS

The results of the evaluation will be documented in a report and will include such statistics and information as the following:

- Percent difference in TOC when decisions are made with and without using RSC*Model*
- Percent difference in TOC when the RSC*Model* optimizer is used
- Average time to learn how to use RSC*Model*
- Level of difficulty in using RSC*Model*
- List of PM suggestions and other findings for improving RSC*Model*

A.2 Preliminary Outline for Method to Evaluate Effectiveness

(Revised 31 October 2011 for inclusion in thesis)

Outline for Evaluation of RSC*Model* Effectiveness

OBJECTIVE: Compare the ability of supply chain experts to effectively make supply chain risk management decisions that minimize total cost of ownership of the supply chain with and without the use of RSC*Model*.

APPROACH: Program Managers (PM) are provided with a "realistic" baseline supply chain and two "typical" disruption scenarios ("typical" meaning conceivable supplier disruption scenarios): (1) a temporary and minimal supplier failure and (2) a permanent and highly disruptive failure. PMs are asked to determine the most cost-effective way to manage the disruption scenarios. The effectiveness of RSC*Model* is then evaluated with feedback in the form of expert opinion and data gathered from the PMs through surveys and interviews. Effectiveness is measured along three key dimensions:

4. Ability to minimize supply chain total cost of ownership
5. Ease of use
6. Ease of learning

PROCEDURE: Develop the baseline disruption scenarios based on the current *sample part and supply chain used in* RSC*Model development*. All baseline supply chain information would be the same in both scenarios except for two different disruption scenarios. The two disruptions presented would be something like the following:

Scenario 1

Minor disruption – 1 week shut down of a major supplier.

As the program manager, you are aware that tension between union employees and management at one of your major suppliers has been rising over the last few weeks. It has come to your attention that the situation has turned bad enough that it could threaten supply from that supplier. You expect there is a 75% chance that sometime in the next 2 months the labor dispute will result in a 1 week strike (and therefore complete supply shut down) from that supplier.

Scenario 2

Major disruption – Permanent shut down of a critical supplier.

As the program manager, you are aware that due to a recent economic crisis, one of your critical suppliers is close to complete financial failure. This supplier disruption risk is of great concern to you and you want to know the best strategy to manage the risk. You expect the supplier could permanently shut down as early as next week. This would cut off all future supply from this supplier and you immediately have no access to any of the supplier's inventory.

Risk management strategies are developed for comparison in four phases. Each expert is presented with the supply chain data and predefined disruption risk scenarios and is asked to indicate the approach or solution (i.e. supply chain configuration and coordination decisions) he would use to manage the risk in three phases:

- First, the PM is asked to develop a risk management strategy through any means desired (i.e. using current tools, methods, and techniques) and with no limitations on the management strategy, except that the strategy must address only impact reduction (not risk probability or severity reduction or elimination).
- Second, the PM is again asked to develop a risk management strategy through any means desired, but is limited to a strategy based on the available parameters in RSC*Model* (replacement suppliers, inventory, retainer capacity, consignment, etc.).
- Third, the PM is asked to develop a risk management strategy using RSC*Model* and its scenario analysis capability.

A fourth risk management strategy is then developed independent of the PM:

- Fourth, RSC*Model* is used to identify the "optimum" supply chain management strategy through the model's optimization capability.

REQUIREMENTS, ASSUMPTIONS and LIMITATIONS:

- Need participation and cooperation of 3 (at minimum) program managers willing to participate in evaluation process, executing tasks and providing feedback in a timely manner.
- Supply chain and disruption scenarios must be presented in a simple, easily comprehensible way.
- Must provide PM with standard instructions or a standard briefing on the use of RSC*Model*.
- Must provide PM with RSC*Model* installation files and instructions.
- Must provide a resource where the PM can reach out for help on program or model setup and use.
- Assumption is that all the provided supply chain data would be known by the PM, therefore we just give it to them

- Need to provide all the information needed for the PM to create the baseline scenario in RSC*Model*, which includes all the information the PM would need to fill in all the required data input tables (although, it doesn't need to, nor should it, be presented to the PM in a form that is exactly how it would be entered in RSC*Model*).
    - Supplier Information
        - Identify and "define" all available suppliers, up to 16 in total (should come from *sample supply chain used in* RSC*Model development,* although we may need to include some modifications and addition of fictitious optional suppliers as replacements for risk management strategies)
        - Active dates for all "active" suppliers will be at start of simulation timeline
        - No specific supplier deactivation will be presented as the PM will have to choose whether to analyze with a stochastic approach through the supplier risk table or with a defined disruption date through the supplier risk table
        - Included in the supply chain schematic (see 'Supply Chain Configuration') would be supplier names, subcomponents produced, base production rates, startup inventory, ordering cycle, etc.
        - Available suppliers are constant, PM cannot introduce new suppliers outside of the defined scenario (this is necessary to bound the experiment)
        - No surge and sag capability of suppliers (because this could affect the disruption scenario and impact as well as the available recovery strategies)
    - Purchase Orders
        - Need to determine dates/timeline for test case (possibly use what was found through surveys for *sample part used in* RSC*Model development*)
        - A constant PO pattern for the length of the simulation will be provided to keep it simple and since no surge or sag conditions are needed (could use the baseline data from RSC*Model agility analysis*)
        - A table with the PO pattern will be provided to the PM with the scenario
    - Business Costs
        - Any business costs associated with the baseline *sample part and supply chain used in* RSC*Model development* will be provided (these would be constant in all scenarios)
        - Costs associated with disruption scenarios needs to be determined
    - Unit Price Adjustments
        - No foreseeable reason why information pertaining to pricing changes based on surge and sag conditions is needed
    - Supply Chain Configuration *and* Relationships
        - Provide a schematic of the supply chain (possibly a Visio "flowchart") to define the "active" supplier configuration including subcomponents, subcomponent suppliers, BOM quantities, re-order parameters, etc.
        - "De-active" supplier information also included as part of schematic

        - Supply chain must be limited to 12 suppliers (per RSC*Model* functionality)
    - Supplier Risk (Management)
        - Failure probabilities and duration defined for PM
        - Risk probability and severity (duration) values are fixed.
        - PM determines the recovery strategy by choosing recovery strategy variable "levels" (replacement suppliers, inventory, retainer capacity, and consignment)
- This method looks only at effectiveness when used in a proactive approach for an existing supply chain (limitation of study)
    - Provides limited ability to assess improvement of supplier selection decisions compared to "three bids and a buy approach"

DATA COLLECTION AND EVALUATION:

Minimization of Supply Chain Total Cost of Ownership

The various risk management strategies developed by the PMs and through RSC*Model* optimization are compared to evaluate the effectiveness of RSC*Model* in helping make cost-effective risk management decisions. The PMs are also surveyed (and possibly interviewed) to obtain feedback on the approach used for strategy development and expected outcomes.

The response of each expert for phase 2 and 3 is evaluated on a total cost basis with the RSC*Model* tool and compared to the "optimal" solution developed with the RSC*Model* tool. For phase 1 and 2, an accompanying questionnaire asks each PM to indicate the method used to arrive at the chosen solution/strategy (i.e. why and how the solution was chosen), what he expects the outcome of the solution to be (i.e. the expected total cost), and what the PM thinks of the tool's effectiveness.

Ease of Use, Learning and Implementation

As part of an evaluation of the "effectiveness" of RSC*Model* it will be beneficial to collect data and feedback on how easy the tool is to use, adopt and implement. These dimensions of "effectiveness" will be evaluated through surveys administered to the PMs after completion of all phases of strategy development are complete.

Surveys will be administered online using Google "Forms" to permit ease of completion and data collection. Surveys will include open-ended and rating scale questions. For ease of implementation, the PM is asked questions regarding the time and effort required to install the RSC*Model* application and to start on the analysis for Phase 3. For ease of use, the PM is asked questions regarding the time and effort required to enter the necessary information and perform the analysis to find the best solution. Ease of learning is measured by recording the number of questions each expert has when using the tool after being briefed on standard usage procedures.

Sample Survey Questions

1. How long did it take you to develop the risk management strategy for Phase 1?

________ Hours (Ex. 1.5)

2. How comfortable are you with the strategy developed in Phase 1? (Please Circle One)

Uncomfortable/Hesitant to Execute	1	2	3	4	5	Very Comfortable/Ready to Execute

A.3 Original RSC*Model* Assessment Survey with Objectives

RSC*Model* Assessment Survey - Risk

INTRODUCTION:

RSC*Model* (*Risk Supply Chain Model*) is a recently developed tool for assessing and minimizing the cost impact of supplier disruption risk on a supply chain. This survey is for the purpose of getting your feedback on the usability and value of RSC*Model*. It is assumed that you have completed the online RSC*Model* tutorial and consulted the user guide. If not, please do so before proceeding with this survey.

(NOTE: RSC*Model also has functionality to assess and minimize the cost impact of a surge or sag in demand on a supply chain, called 'Agility' analysis. The 'Agility' functionality is addressed in a separate survey titled '*RSC*Model Assessment Survey – Agility')*

Please indicate your prior level of experience using supply chain analytic tools. (Check one)

No Experience	*Novice*	*Moderate Experience*	*Experienced*	*Expert*
☐	☐	☐	☐	☐

Objective: Assess survey respondent's prior experience with supply chain analytic tools, providing "context" to other responses.

INSTRUCTIONS:

Please indicate the degree to which you agree or disagree with the following statements about RSC*Model:*

1. **It was clear from the tutorial, user guide and use of the tool that the purpose of RSC*Model* is *to assess and minimize the cost impact of supplier disruption risk on a supply chain*.**

Strongly Disagree	*Disagree*	*Neither Agree nor Disagree*	*Agree*	*Strongly Agree*
☐	☐	☐	☐	☐

Objective: Assess ease of use of RSC*Model*; specifically, understanding RSC*Model*'s intended objective.

Comments/Suggestions:

2. **RSC*Model*'s user interface is easy to understand and use considering the complexity of the issues the tool addresses.**

Strongly Disagree	*Disagree*	*Neither Agree nor Disagree*	*Agree*	*Strongly Agree*
☐	☐	☐	☐	☐

Objective: Assess ease of use of RSC*Model*; specifically, the user interface.

Comments/Suggestions:

3. **I can more effectively determine how to minimize the *cost impact* of supplier disruption risk on a supply chain using RSC*Model* than with other methods I've tried.**

Strongly Disagree	*Disagree*	*Neither Agree nor Disagree*	*Agree*	*Strongly Agree*
☐	☐	☐	☐	☐

Objective: Assess *value-adding* potential of RSC*Model*; specifically, improvement in ability to minimize TOC.

Comments/Suggestions:

4. **The output reports produced by RSC*Model* provide all the information I need to fully understand the *impact* of supplier disruption risk on supply chain *performance* and *cost*.** (Available reports: TOC, supplier inventory levels, service level, current production level, units produced, and supplier event log)

Strongly Disagree	*Disagree*	*Neither Agree nor Disagree*	*Agree*	*Strongly Agree*
☐	☐	☐	☐	☐

Objective: Assess ease of use and ability to assess and minimize cost impact of supplier disruptions with RSC*Model*; specifically, ease of interpretation and usefulness of output reports.

Comments/Suggestions:

5. **The solution options provided by RSC*Model* for reducing the *cost impact* of supplier disruption risk on a supply chain represent all, and only, the most significant options that should be considered.**
   (Available solution options: *supplier replacement, multiple sourcing, inventory, retainer capacity, & inventory on consignment*)

Strongly Disagree	*Disagree*	*Neither Agree nor Disagree*	*Agree*	*Strongly Agree*
☐	☐	☐	☐	☐

   Objective: Assess validity and *value-adding* potential of RSC*Model*; specifically, validity of solution options in providing guidance in decision making.

   Comments/Suggestions:

6. **RSC*Model* captures all relevant issues and presents an appropriate process to accurately *assess* the *impact* of supplier disruption risk on supply chain *performance* and *cost.***

Strongly Disagree	*Disagree*	*Neither Agree nor Disagree*	*Agree*	*Strongly Agree*
☐	☐	☐	☐	☐

   Objective: Assess overall validity of RSC*Model* as a decision support tool.

   Comments/Suggestions:

7. **What specific suggestions would you make for improving RSC*Model*?**

A.4 Revised and Condensed RSC*Model* Assessment Survey

RSC*Model* Assessment Survey -- Risk

RSC*Model* (*Risk Supply Chain Model*) is a supply chain analytic tool for (1) enhancing supply chain agility and (2) mitigating supplier disruption risk. The purpose of this survey is to gather feedback on the usability and value of RSC*Model* with respect to mitigating supplier disruption **risk** in a supply chain, where mitigation efforts are limited to reducing the consequences of one or more suppliers losing their capacity to deliver requested goods for a determinate or indeterminate amount of time. It is assumed that you have either seen a demonstration of the tool, consulted the user guide, and/or used the tool with a test case. If not, please do so before proceeding with this survey.

Please respond to the following questions pertaining to the modeling features and capabilities of RSC*Model* for **supplier disruption risk mitigation**:

1. **What was your level of exposure to RSC*Model*'s risk mitigation modeling capabilities? (Check all that apply.)**

Saw Demonstration	*Read User Guide*	*Actually Used the Tool*
☐	☐	☐

2. **Prior to your exposure to RSC*Model*, what was your level of experience with supply chain analytic tools for analyzing supply chain risk?**

Low	*Medium*	*High*
☐	☐	☐

Comments:

3. **How do you rate the overall effectiveness of RSC*Model* in helping one understand and mitigate supplier disruption risk?**

Low	*Medium*	*High*
☐	☐	☐

Comments/Suggestions:

4. **How would you rate the level of difficulty to understand and use RSC*Model* to define different risk mitigation scenarios?**

Low ☐ *Medium* ☐ *High* ☐

Comments/Suggestions:

5. **To what extent does RSC*Model* allow for all relevant input factors and solution strategies to be taken into account when defining risk mitigation scenarios?**

Low ☐ *Medium* ☐ *High* ☐

Comments/Suggestions:

6. **How would you rate the level of difficulty to read and interpret RSC*Model*'s output reports for assessing risk mitigation scenarios?**

Low ☐ *Medium* ☐ *High* ☐

Comments/Suggestions:

7. **How would you rate the usefulness and relevance of RSC*Model*'s output reports for making supplier disruption risk related decisions?**

Low ☐ *Medium* ☐ *High* ☐

Comments/Suggestions:

8. What specific suggestions would you make for improving the modeling and analysis features and capabilities of RSC*Model* for mitigating supplier disruption risk?

APPENDIX B EXECUTIVE SUMMARY OF INTEGRATION POTENTIAL

(Revised 16 November 2011 for inclusion in thesis)

Supply Chain Analytical Tool Summaries

Product Names: RANGER, PrimeMap, PrimeSupplier, RSC*Model*

Introduction

In April 2011 *the Lead Non-Profit Organization* and BYU held conference calls with the RANGER product group at ___ and *an official at* NASA, project lead for PrimeMap and PrimeSupplier. The purpose of these meetings was to:

1. Get a product overview of each product
2. Obtain answers to specific questions about each product submitted to the relevant representatives
3. Explore potential integration opportunities with the RSC*Model* (*Risk Supply Chain Model*) tool

With the information from these conference calls, follow-up inquiries, and internet searches a preliminary assessment of each product was prepared, and integration possibilities with RSC*Model* and recommended next steps were identified. Following is a condensed summary of each tool.

RANGER

RANGER (Risk Assessment for Next Generation Supply Chain Readiness) is a *DoD* funded, adaptable risk assessment and identification tool. It uses commercially available AgenaRisk software to aggregate risk probabilities for one or more of 10 possible performance "drivers" based on Bayesian Network algorithms and selected risk elements from a dynamic, research based risk taxonomy of 155 risk elements (such as likelihood of disaster, etc.). As such, it can quantitatively *describe* the effect of user selected risk probabilities on a performance driver. Conversely, it can also be used to quantitatively *prescribe* risk probabilities to achieve a target resultant risk probability for a selected performance driver. A proof of concept model is complete and the product is now in a Beta testing phase. Gathering and inputting data to describe supply chain risks is largely a manual process and requires significant upfront effort and expertise. Future developments are aimed at improving the user interface to make the product easier to use. The supply chain data and probability analysis are stored in the RANGER database and should be accessible through the import/export features of Agena.

In sum, RANGER provides an effective method for accurately identifying supplier failure risk probabilities at each node in the supply chain and for quantifying the propagation of these probabilities both forward and backward in the supply chain.

PrimeMap & PrimeSupplier

NASA's Prime Products include two separate but related "next generation supply chain applications," PrimeMap and PrimeSupplier, both aimed at supplier risk identification.

PrimeMap

PrimeMap is a web-accessible supply chain and disaster visualization and assessment tool using commercial mapping software and a custom user interface developed by Advanced Core Concepts. PrimeMap does the following:

- uses real-time data feeds for current and historic disasters to identify potential impacts of disasters on the supply chain
- provides various filtered views of the supply base based on congressional districts, supplier demographics, programmatic information, etc.,
- provides access to supplier specific information on performance, capabilities, ratings, and other measures.

PrimeSupplier

PrimeSupplier is a supplier "stability index" model that produces a quantified Total Risk Factor for each supplier based on risk factors associated with economics, supply chain operation and supply chain readiness. PrimeSupplier is currently an "internal" NASA application that appears to use Microsoft Excel for the primary user interface.

Future developments aim to link the two applications and feed PrimeSupplier risk data to the supplier performance tab within PrimeMap, with "The Map" from PrimeMap being the primary visual anchor. Both tools hold promise for commercial application beyond aerospace and defense but remain very NASA centric and need some further technical development. Neither product currently supports simulation although future development efforts aim for integration of Monte Carlo and Discrete-event simulation methods which could help provide for optimized programmatic and configuration decisions and add a dynamic aspect to risk identification and assessment.

RSC*Model*

The Lead Non-Profit Organization has developed a working prototype of a "predictive analytic" supply chain analysis tool for determining the most cost-effective management strategy for dealing with supplier disruption risks and demand fluctuation scenarios. The tool is called RSC*Model* (*Risk Supply Chain Model*) and is built on ProModel's discrete-event simulation technology using Microsoft Excel as the primary user interface and data input mechanism. RSC*Model* dynamically simulates different supplier disruption and demand fluctuation scenarios in order to find the optimum supply chain management strategy based on total cost of ownership, service level, and other production measures. RSC*Model* currently does not interface with any other programs or databases although ProModel and Excel both have a diverse set of user interface options that enable data to be exchanged with other applications and government funded supply chain analysis tools, such as RANGER, PrimeMap and PrimeSupplier.

Integration Opportunities

While each of the three product sets described above has a different focus and approach to assessing and mitigating supply chain risk, they all complement each other in ways that can produce a synergistic solution. For example, one possible integration scenario of all three software sets is for the Prime products to feed RANGER various risk probabilities based on real world information. RANGER could then use this data to calculate resultant risk probabilities that can then be feed to RSC*Model*. Additionally, the Prime products could feed risk severity information directly to RSC*Model*. RSC*Model* could then perform a dynamic assessment of alternative risk management strategies using discrete-event simulation. The RSC*Model* recommendations could then be fed back into RANGER or the Prime tools to do further probability reduction studies. The Prime tools further provide supplier health information that can be fed into RSC*Model* to assess the agility of the supply chain.

The synergistic relationship between these tools needs to be further explored to fully leverage past and future investments in tool development. Future development should focus on these integration opportunities to reduce duplication of effort in identifying and modeling supplier information and supply chain network relationships. Questions need to be answered regarding which method of data sharing is the best, how future development of each tool may create additional synergies, and what industry partners may be interested in participating in an integration proof-of-concept development project.

APPENDIX C RANGER QUESTIONS AND REPORT

C.1 RANGER Survey Questions

1. How is this tool intended/designed to be accessed? (stand-alone, client-server, Software as a Service, etc.)
2. What is the current state of development of this product? (official release, in alpha or beta testing, in development, etc.)
3. What specific risk factors does this tool assess? (economic, natural disaster, etc.)
4. How are these risk factors measured? (ranking, scale, etc.)
5. In what ways can these metrics be accessed (database, Excel, through an API, etc.), and is there good documentation on this?
6. What data must be input into the tool to get meaningful output? (supplier location, years in business, etc.)
7. What form must this data be in and how is it entered? (manual entry, link to database, API, etc.)
8. Who is currently using the tool and what has been the response?
9. What significant future enhancements are planned for this tool?

C.2 RANGER - Product Summary and Integration Assessment Report

Revised May 17, 2011 *(Revised 16 November 2011 for thesis)*
Authors: B. J. Saunders and Charley Harrell

RANGER Product Summary and Integration Potential with RSC*Model*

Product Name: Risk Assessment for Next Generation Supply Chain Readiness (RANGER)
Contacts: ___________ – ___, Program Manager for RANGER
_____________ – ___, Technical lead for RANGER
___________ – ___

Introduction

On April __, 2011, *the Lead Non-Profit Organization* and BYU held a conference call with the RANGER product group at ___ for the purpose of (1) getting a product overview of RANGER, (2) obtaining answers to specific questions that had been submitted to ___, and (3) exploring potential integration opportunities with RSC*Model* (*Risk Supply Chain Model*) tool.

Questions and Answers

Below is a summary of the answers received in response to the questions submitted to ___. Included in some of these answers is information BYU obtained through an internet search.

1. **How is this tool intended/designed to be accessed? (stand-alone, client-server, Software as a Service, etc.)**
   RANGER uses a product called Agena as its underlying modeling and analysis tool. Since Agena runs on either a desktop (stand-alone) or in a client-server mode, the RANGER tool can be adapted to run either locally via the desktop application or in a distributed environment via a client-server relationship. (Additional information on the AgenaRisk Enterprise software is included in the 'General Agena Information' Section.)

2. **What is the current state of development of this product? (official release, in alpha or beta testing, in development, etc.)**
   The RANGER program is in the beginning of a Beta testing phase (Phase 2). Phase 1 (Requirements Definition and Alpha testing) has been completed, which included: initial research for identification of supply chain risks and creation of a supply chain risk taxonomy, evaluation and selection of a Bayesian Network modeling tool (as opposed to a Monte Carlo tool), and creation of a proof-of-concept model. In Phase 2 the project began using Agena as the "host" engine for RANGER, and the team is now ready for pilot and implementation testing. As part of Phase 2 and beyond, further enhancements to the tool are in the works as discussed in question 9.

3. **What specific risk factors does this tool assess? (economic, natural disaster, etc.)**
   Based on research being carried out with the University of Kentucky, a risk element taxonomy has been created and is currently made up of 155 risk elements. A risk element might be the financial

condition of the supplier or the likelihood of a natural disaster. This taxonomy is “dynamic” and is updated on a quarterly basis with new insight from ongoing research. Possibly the most important and novel aspect of the RANGER tool is this taxonomy of risk elements, such that the tool uses real risk factors backed by academic research in its analysis.

The current scope of the RANGER product is focused on risk assessment, including: risk identification, risk analysis, and risk evaluation.

4. **How are these risk factors measured? (ranking, scale, etc.)**
   Risk elements are ranked by the customer in terms of the significance of their impact on the outcome of interest. The risk elements may be ranked on any appropriate measure as defined by the user. Possible examples include ranking risk elements from 1-5, 1-10, true/false, yes/no, high-med-low, etc. The highest ranking elements are then considered in terms of their probability of occurrence. It wasn’t apparent how this probability is determined (formula, heuristic, interviews, guestimate, etc.). Once a probability of occurrence is determined for each supplier, Agena analyzes the probability chains to calculate a resultant probability that the customer will be impacted.

   It was indicated there are 10 different performance “drivers” that can be assessed with the tool. These appear to be what we might consider as performance metrics that measure the system response based on selected risk factors. One of these output metrics, for example, is “Delivery” (probability of on-time delivery). The remaining 9 “performance drivers” were not disclosed. Other outputs include Tornado diagrams, heat maps, and tree maps, once again, all related to probability measures.

   One advantage of the Bayesian Network approach used by RANGER and Agena is the ability to “back propagate” probabilities. This means that output results from the analysis can include not only resultant probabilities, but also the prescribed source-node probabilities needed to achieve a target resultant probability. For example, a 100% probability of on-time delivery for the customer can be entered and the tool will determine the needed supplier probabilities of on-time delivery of their parts that will ensure this resultant probability for the customer.

5. **In what ways can these metrics be accessed (database, Excel, through an API, etc.), and is there good documentation on this?**
   All the identified risks and data about the supply chain are stored in the native Agena model. With the basic desktop version of AgenaRisk, it is uncertain how or if model data, such as output metrics, can be accessed outside of the tool. Based on general information about the enterprise edition of AgenaRisk, data can be accessed through export files, databases, and APIs, as explained in the ‘General Agena Information’ section.

6. **What data must be input into the tool to get meaningful output? (supplier location, years in business, etc.)**
   There is a significant amount of upfront work required to get the needed information required for use of the tool. This work includes (1) selection of risk factors from the taxonomy, (2) the ranking of risk factors on a scale of 1-5, (3) creation of a project specific causal model based on a simplified risk taxonomy, and (4) population of node probability tables based on data from interviews, surveys,

database, etc. Building the model is time consuming, although once established, future use and upkeep requires less time and effort.

7. **What form must this data be in and how is it entered? (manual entry, link to database, API, etc.)**
The RANGER product does not currently use or support live data feeds but this is an option that is being explored for future development. This seems to indicate that currently, input data is fed into the model via manual methods. Information on the enterprise version of AgenaRisk indicates that data feeds via files, databases, and APIs are possible.

8. **Who is currently using the tool and what has been the response?**
The RANGER team has received considerable interest from mid- and senior-level management in various commercial entities. As of yet, however, there still seems to be certain barriers to overcome, such as ease of use, in order for the tool to become widely adopted. Current commercial partners are GE and Boeing.

9. **What significant future enhancements are planned for this tool?**
A working prototype has been created with the Agena software, but the current user interface requires considerable training and domain expertise for creation and use of the model. Part of the future Phase 2 work is to create a more viable and intuitive user interface for the tool. Beyond Phase 2, additional industrial test cases need to be performed before being released as a commercial product. Increased support for live data feeds are possible future enhancements as well.

General Agena Information

Agena is the modeling and analysis product used to develop the RANGER tool. Agena was selected by the RANGER team because of its established capability in modeling Bayesian Networks and its commercial availability. Agena had been used previously in financial and medical markets, but lacked practical application for use as a supply chain tool. The following summary information on *Agena: Bayesian Network and Simulation Software for Risk Analysis and Decision Support* was obtained from the AgenaRisk website[1] (the software package is referred to as AgenaRisk).

Company Background

- Company founded in 1998 in the UK. Founders and senior management have ties to University of London.

Product Description

According to the website, *"AgenaRisk enables decision-makers to measure and compare different risks in a way that is repeatable and auditable. The AgenaRisk solution includes predictive analytics and scales up to organisational-level risk monitoring and assessment. It is ideal for risk scenario planning. AgenaRisk provides decision support solutions that include: Operational risk, Business continuity, Strategic planning and investment decision making, Management of complex*

[1] http://www.agenarisk.com/

projects, Procurement of critical military assets, Ensuring the safety and reliability of critical systems."

The Agena product *"[supports] both diagnostic and predictive reasoning about uncertainty using risk maps, otherwise known as Bayesian networks [for modeling causal relationships]*"

It utilizes "*hierarchical modelling as an alternative to Monte Carlo Markov Chains (MCMC)"*
It also supports "d*ynamic modelling of time-based or evolving systems (e.g. Markov analysis)"*

Software Details

- 30-day desktop trial can be downloaded from Agena website
- Two version of AgenaRisk software available
    - *Desktop*
    - *Enterprise* – a software development kit (SDK) that allows users to incorporate AgenaRisk functionality and models into their own applications, link them to external data sources, export results to information portals (via a web server) and build sophisticated application specific data structures (Meta Data)

External Connectivity

A Java API appears to be available to "support … Relational Modelling and Interfaces to databases and flat files," but only for the Enterprise version (vs. the desktop version) of the Agena software.

Excerpt from AgenaRisk website:

AgenaRisk Enterprise comprises three components:

1. Database Connectivity —Connect to any JDBC or ODBC compliant data source including:
    - CSV files and Excel spreadsheets (Import and export of data from Agena models is available via CSV files)
    - Personal databases such as Microsoft Access
    - Open source databases such as MySQL and Postgres
    - Enterprise platforms such as Oracle and SQL Server
2. Application Programming Interface (API) — This is a set of java routines that let you directly create, edit and execute AgenaRisk models as a part of a client server, webs services or desktop enabled application.
3. AgenaRisk Application Generator (AAG) — This allows you to generate large and complex risk models directly from relational databases or text file schemas and then use these models within a wider system or directly use them within the AgenaRisk Desktop.

RANGER Strengths and Weaknesses

Product Strengths

- RANGER is built on Agena, which is a commercially available software product.
- Identifies an extensive list of risk factors to consider (155) and ten different performance drivers that can be assessed.
- Models can be created at different levels of detail which makes it adaptable to a wide range of applications, from small work cells to global supply chains.

- The Bayesian network method quantitatively *describes* the resultant effect of risk probabilities, and also quantitatively *prescribes* risk probabilities to achieve a target resultant risk probability.
- RANGER provides a methodology for evaluating risk avoidance and mitigation strategies by analyzing their effect on the performance driver of interest.

Product Weaknesses

- Complexity of setup requires time and resource commitments, including possible expenditure for consulting services.
- The risk analysis performed by RANGER is a static analysis providing only the probability of an event. It does not account for the timing of events, and state changes over time that may be caused by the event.

Relationship between RANGER and RSC*Model*

The Lead Non-Profit Organization is developing a tool designated as RSC*Model* which looks at agility and disruption risk in a supply chain. Since RANGER really doesn't address supply chain agility, here we compare the two products only in terms of how each addresses the element of risk. We also look at how the two products complement each other.

Comparison of RANGER and RSC*Model* Inputs and Outputs

RANGER and RSC*Model* are two different tools designed to solve two different, though related, problems as it pertains to supply-chain risk. RANGER is designed to determine the resultant probability of several different types of risk events (e.g., late deliveries, cost overruns, etc.) and what corrective measures can be taken to reduce this probability. RSC*Model*, on the other hand, is designed to look at the impact on performance (service level, cost, etc.) that supplier interruptions, demand forecasts, and different risk mitigation strategies can have on the supply chain. RSC*Model* uses probabilities, like RANGER, but the only risk probability it uses is the risk of a supplier interruption. RSC*Model* doesn't compute any resultant probabilities, but rather resultant performance (service level, cost, etc.). Additionally, RANGER can pinpoint where the greatest risk factors are in a supply chain that impact overall risk. RSC*Model*, on the other hand, helps identify which remedial strategy in an environment of supplier failure risks that has the greatest impact on supply-chain performance as measured by cost, service level, etc.

How RSC*Model* could benefit from RANGER

Though RSC*Model* uses the probability of a supplier interruption to predict supply chain performance, it has no systematic method of identifying the factors that contribute to supplier interruption, nor does it have a reliable method of quantifying the probability associated with a disruption. Yet these probability values are essential to generating accurate simulations. RSC*Model* could benefit from RANGER by being able to access its supplier failure probabilities.

How RANGER could benefit from RSC*Model*

While users benefit from RANGER's ability to identify key risk factors which leads them towards solutions for reducing or eliminating these factors, users may still want to fine tune the solution by seeing how it impacts supply-chain performance in terms of cost, service level, etc. RSC*Model* could complement RANGER by helping users formulate effective strategies for dealing with risks through a simple and intuitive simulation model.

Future Possible Benefits
In the future, RSC*Model* may look at other risk factors in addition to supplier failure (e.g., product quality, late delivery, etc.). This would open up additional opportunities for RANGER to leverage its models by providing RSC*Model* with accurate probabilities for these risk factors.

Recommended Next Steps

In follow-up to the initial phone conference with ___, it may be advantageous to further explore technology integration opportunities between ___ and *the Lead Non-Profit Organization*, and how each can leverage the strengths of the other. Specific research questions might include:

- How could both technologies be synergistically related (e.g., RANGER for initial risk assessment and RSC*Model* for subsequent risk management)?
- What types of data sharing can both products benefit from?
- How would such data sharing occur?
- Is there a potential industry partner that would be willing to collaborate in an integration proof of concept?
- In the future are there other performance drivers, besides delivery failure, that may be worth simulating at an operational level using RSC*Model*?

Appendix: Background Information on Monte Carlo and Bayesian Simulation

Monte Carlo methods "rely on repeated random sampling to compute … results" and "tend to be used when it is infeasible to compute an exact result with a deterministic algorithm." They are "especially useful for simulating systems with many coupled degrees of freedom" and to "model phenomena with significant uncertainty in inputs, such as the calculation of business risk."[2]

Bayes' theorem is a simple mathematical formula used for calculating conditional and inverse probabilities[3,4]. The simple version of Bayes' theorem can be represented as:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

This allows you to calculate the conditional probability of 'A' given 'B' by knowing the probability (likelihood) of 'B' given 'A' and the marginal, or unconditional, probabilities of 'A' and 'B'. So, for example you can calculate the probability of a delivery being late given that it is shipped via rail, P(A|B), by knowing the probability that the delivery is via rail given that it is late P(B|A), the probability that a delivery is late P(A), and the probability that the delivery is via rail P(B), where event A is that the delivery is late and event B is that the delivery is via rail.

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[2] http://en.wikipedia.org/wiki/Monte_Carlo_method
[3] http://plato.stanford.edu/entries/bayes-theorem/
[4] http://en.wikipedia.org/wiki/Bayes%27_theorem

APPENDIX D PRIMESUPPLIER AND PRIMEMAP QUESTIONS AND REPORT

D.1 PrimeMap and PrimeSupplier Survey Questions

1. How is each tool intended/designed to be accessed? (stand-alone, client-server, Software as a Service, etc.)
2. What is the current state of development of each product? (official release, in alpha or beta testing, in development, etc.)
3. What is the relationship (extent of integration) between the PrimeSupplier and PrimeMap products?
4. What specific risk factors does each tool assess? (economic, natural disaster, etc.)
5. How are these risk factors measured? (ranking, scale, etc.)
6. What output metrics are provided and how is this data interpreted? (Economic Stability Indicator (PrimeSupplier), natural disaster effects on suppliers (PrimeMap), etc.)
7. In what ways can these risk factors and metrics be accessed (database, Excel, through an API, etc.), and is there good documentation on this?
8. What data must be input into each tool to get meaningful output? (supplier location, years in business, etc.)
9. What form must this data be in, what is the typical source, and how is it entered? (manual entry, link to database, API, etc.)
10. Who is currently using these tools and what has been the response?
11. What significant future enhancements are planned for these tools?
    - What further development/customization of the GUI or deeper program elements would be needed to make it useful for other uses outside of NASA?

D.2 Prime Products – Product Summary and Integration Assessment Report

Revised May 17, 2011 *(Revised 16 November 2011 for thesis)*
Authors: B.J. Saunders, Charley Harrell, Jordan Ellingson

NASA Prime Products - Product Summary and Integration Potential with RSC*Model*

Product Name(s): PrimeMap and PrimeSupplier
Contact: *Project Manager*, Supply Chain Manager at NASA; Kennedy Space Center Computational Sciences Group for Modeling and Simulation

Introduction

On April _, 2011, *the Lead Non-Profit Organization* and BYU held a conference call with *Project Manager* of NASA, project lead for PrimeMap and PrimeSupplier, for the purpose of (1) getting a product overview, (2) obtaining answers to specific questions that had been submitted to *Project Manager*, and (3) exploring potential integration opportunities with RSC*Model* (*Risk Supply Chain Model*) tool.

Questions and Answers

Below is a summary of the answers received in response to the questions submitted to *Project Manager*. His responses have been augmented with additional information BYU obtained through an internet search and from notes on previous inquiries made by ___________.

1. **How is each tool intended/designed to be accessed? (stand-alone, client-server, Software as a Service, etc.)**
   <u>*PrimeMap*</u>
   The geographic mapping functionality of PrimeMap is built on commercially available mapping software (what appears to be Microsoft Virtual Earth, now known as Bing Maps). The rest of the PrimeMap interface (menus, relational maps, and supplier information pages) is a custom, web-based application that runs inside and is accessed via an internet browser. The program interface was developed by Advanced Core Concepts which offers what appears to be a very similar commercially available product in several modules called Visual Supplier Assessment & Analysis Modules (VSAAM)[1].

   <u>*PrimeSupplier*</u>
   Unlike PrimeMap, PrimeSupplier is currently an internal application and is not web-accessible. Although no visual demonstration of the actual PrimeSupplier product was made during the conference call, from other internet sources with information on PrimeSupplier it appears that the basic user interface of the preliminary "v1.0" version of the tool was based on and runs inside

[1] http://www.advcoreconcepts.com/Products.aspx

Microsoft Excel, although it not certain if "v2.0" continues to use Excel. Developments underway to link PrimeMap and PrimeSupplier aim to include PrimeSupplier risk information on the "Performance" tab inside PrimeMap.

2. **What is the current state of development of each product? (official release, in alpha or beta testing, in development, etc.)**
PrimeMap
PrimeMap appears to be a fully functional product, with what appears to be a commercially available version offered by Advance Core Concepts, the primary developer, called Visual Supplier Assessment and Analysis Modules (VSAAM). PrimeMap currently does not include simulation analysis but the intent is to support discrete-event simulation methods in the future. It appears that 3rd party simulation tools have not yet been used with PrimeMap, although it has been used with other applications within NASA. The nature and purpose of those applications is unknown.

PrimeSupplier
PrimeSupplier has been through at least two development phases with a version 1.0 and now the current version 2.0 of the application being developed. The University of Alabama in Huntsville has been involved in at least the last phase of development which just completed and pending approval of a final round of funding the program is moving to the next phase for future enhancements as explained in question 11. The completed phases of development have demonstrated its capabilities to assess and output risk data and presents a "bold vision" for risk projection capabilities for supply chains. The application, however, is still NASA centric and is in need of further technical development.

3. **What is the relationship (extent of integration) between the PrimeSupplier and PrimeMap products?**
The full extent of current integration between the two tools isn't clear but current and future development efforts aim to link the two programs such that PrimeSupplier can feed risk reference/indicator data into the "Performance" tab of PrimeMap. A potential capability of the link to exchange supply chain structure data was also indicated. "The Map would be the primary visual/anchor."

4. **What specific risk factors does each tool assess? (economic, natural disaster, etc.)**
PrimeMap
PrimeSupplier and PrimeMap were developed for the purpose of assessing the impact on the supply base of shuttle transition activities. PrimeMap was specifically developed to help identify suppliers and relationships across the NASA supply base. The PrimeMap software allows for the visual representation of suppliers based on geographic location and/or relationship in the supply chain. Additionally, the software provides visualization of natural disasters including hurricanes, earthquakes, wildfires, or man-made disasters by geographic area. The product also allows suppliers to be filtered by congressional district and by demographic criteria including small, women-owned, veteran-owned, service disabled veteran-owned, and small disadvantaged-owned businesses. The combination of supplier location, relationship data and disaster risks allows the user to identify and assess the potential supply chain risks on a supplier, product, program, and agency-wide level.

PrimeSupplier

PrimeSupplier is an "economic stability index model" and takes into account not only financial risks but also programmatic and demand data. In calculating a Total Risk factor for each supplier, the program uses risk factors in three areas: financial, operational, and supply chain.

5. **How are these risk factors measured? (ranking, scale, etc.)**

PrimeMap

Information on risk factors in PrimeMap appears to be primarily a visual representation of suppliers based on geographic location in relation to disaster potential and/or current disasters. The extent of impact to other links in the supply chain can also be visualized.

PrimeSupplier

Individual risk factors are measured on a scale from 0-10. It was not explained how input metrics are converted to this risk rating, but the indication is that supplier specific metrics are compared to industry benchmarks. An aggregate risk rating for overall financial, operational, and supply chain risk is calculated from individual risk factor weightings and risk values. The sum of category risk values gives a Total Risk rating for each supplier, which is a weighted average of all individual risk factors values. The weighting and method of calculation appears to be a proprietary function of the tool.

6. **What output metrics are provided and how is this data interpreted? (Economic Stability Indicator (PrimeSupplier), natural disaster effects on suppliers (PrimeMap), etc.)**

PrimeMap

The PrimeMap tool allows the user to select a supplier via the graphical interface (by clicking the supplier's icon) and view data on performance, capabilities, ratings, etc. The details of this data are not known except that PrimeSupplier should provide risk data to be displayed on the performance tab once a link of the two applications is complete. While potential impacts of disasters can be visualized in the tool, it is unknown if quantified output data based on natural disaster or man-made risks is available.

PrimeSupplier

PrimeSupplier provides a Total Risk factor for each company. In "v1.0," this factor was considered an Economic Stability Indicator which provided a "holistic assessment of suppliers' total economic stability" based on approximately 31 data parameters. In "v2.0" of the program further developments to the current total risk factor have been enhanced and it now includes Supply Chain Readiness Level (SCRL). It is not entirely understood how the Total Risk factor is interpreted and what its value indicates, except that the Total Risk factor is a supplier stability index and that in general a higher risk factor indicates a higher level of risk. It is also unknown how Risk Factors can be compared across companies. The Total Risk factor can be used to identify high risk suppliers that are in need of extra support through sustainment or other efforts.

It is hoped that future enhancements of the tool will provide "war game" simulation capabilities to optimize and configure the supply chain. Such future capabilities could add a dynamic element to the risk factor and could provide procurement dates and other programmatic decisions necessary for optimization as outputs.

7. **In what ways can these risk factors and metrics be accessed (database, Excel, through an API, etc.), and is there good documentation on this?**
   PrimeMap
   PrimeMap provides the capability to export supplier data to XLS or PDF formats. PrimeMap does have the capability for automating data extraction, but extraction into XLS or PDF formats is currently not automated.

   PrimeSupplier
   Currently import and export of data appears to be manual. One future improvement indicated for PrimeSupplier is the improvement of program infrastructure to support a digital interface for import and export of data.

8. **What data must be input into each tool to get meaningful output? (supplier location, years in business, etc.)**
   PrimeMap
   PrimeMap currently supports real-time data feeds on natural disasters (hurricanes, wildfires, earthquakes) from sources such as NOAA and the USGS. Supplier specific information is also needed for each supplier in the supply chain. Beyond name, location and supply chain relationship data, it is not known what specific information is needed for each supplier.

   PrimeSupplier
   In formulating an output "Total Risk" factor for individual suppliers, the PrimeSupplier tool uses data on risk factors, or metrics, in three areas: financial, operational, supply chain. These metrics for each supplier include programmatic demand data, such as contract values and percentage of total business, and financial performance data, such as current ratio, debt-equity ratio, and net profit margin. Supply chain data includes data from Supply Chain Readiness Level (SCRL). Information on each individual risk factor in each area is needed as input.

9. **What form must this data be in, what is the typical source, and how is it entered? (manual entry, link to database, API, etc.)**
   PrimeMap
   Current and archived data on hurricanes and earthquakes and current data on wildfires are fed to the PrimeMap application through real-time data feeds from agencies such as the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS). It is not known how supplier specific information is entered in the tool.

   PrimeSupplier
   It is indicated that most of the data that is put into PrimeSupplier is publicly available data or data coming from an ERP system (such as demand data) and other internal sources. Data links and feeds from various external sources such as Dow Jones are planned for a future version.

10. **Who is currently using these tools and what has been the response?**
    PrimeMap and PrimeSupplier were developed in response to the space shuttle transition activities but the applicability of the tools is not limited to aerospace and defense industries. The full extent of current use is unknown but the applications are currently available for use by NASA and the DoD. PrimeMap is currently being applied to other applications. PrimeSupplier is available to other government agencies and NASA is currently seeking commercial partners via licensing opportunities. At least 6 Fortune 500 companies have expressed interest in licensing the PrimeSupplier technology. Some likely candidates for licensing are companies like Boeing, Airbus, Toyota, etc. The applications are patent pending.

11. **What significant future enhancements are planned for these tools?**
    One noted shortcoming of both tools is the lack of data on supplier capacities. It is anticipated that this may be added and leveraged in the future.

    PrimeMap
    Current development is underway to link PrimeSupplier with PrimeMap such that risk data from PrimeSupplier would be available on the "Performance" tab of PrimeMap. Use of the application with third party simulation tools has been discussed but nothing definite has been determined. The application is intended to support discrete-event simulation methods in some form in the future.

    PrimeSupplier
    Several enhancements are still planned for PrimeSupplier and a final round of funding is being sought which would provide for multiple further developments over the next 12 months. PrimeSupplier is intended to use Monte Carlo simulation techniques although this functionality and corresponding graphical user interface elements is currently not supported and the tool primarily relies on manual processes. Monte Carlo simulation techniques for war gaming related capabilities still need to be developed and implemented. It is hoped that "war gaming" simulation functionality can be added in future development to allow the tool to optimize and configure the supply chain and to add a dynamic element to total risk calculations. Specific data sources and methods for efficiently accessing that data in real-time for some risk categories still needs to be added. Integration with *Supplier & Risk Monitor* from Dow Jones is a priority for future enhancement of PrimeSupplier. The link to PrimeMap still needs to be enhanced for access to data on available risk indicators and geographical and relational supplier and supply chain information. Program infrastructure for digital data import and extraction still needs development.

Added Question: What further development/customization of the GUI or deeper program elements would be needed to make it useful for other uses outside of NASA?

Although indications are that the tools are applicable outside of aerospace and defense industries, it is unclear what amount of modification is required for other applications.

PrimeMap Strengths and Weaknesses

Product Strengths

- A good tool for aiding with collaborative demand forecasting and planning.

- Allows user to visualize the supply chain and identify "clusters" and other geographic considerations.
- Provides a visual way to identify and assess supply disruption risks from actual current and historic natural disaster data.
- Application is web-enabled and export of data via XLS or PDF formats is possible.

Product Weaknesses

- It was indicated that it took roughly two years initially to track down all the necessary supplier information for PrimeMap. Time and effort currently required to gather and maintain all necessary supplier information could become prohibitive unless data is currently available via information systems. Access to information is key and "seamless CAD/CAM interface to … enterprise data management tools" (such as SAP, etc.) is vital.
- Simulation capabilities are not yet in place.

PrimeSupplier Strengths and Weaknesses

Product Strengths

- Unlike other tools that only look at financial risks, PrimeSupplier takes into account not only financial risks but also programmatic, demand, and supply chain data.
- Outputs a "Total Risk" factor or stability index ranking for suppliers, which is based on risks in three areas: financial, operational, supply chain. This factor includes a supply chain readiness level.
- Product has support and backing of government agencies.

Product Weaknesses

- Very NASA centric; focus is on projecting risks in government supply chains.
- Suppliers may be reluctant to provide necessary information to support full program functionality.
- Application is currently very manual and labor intensive to use. Functionality for digital import and export of data still needs to be developed.
- It currently does not support simulation, although there are future plans to support Monte Carlo simulation methods, and the current version of the tool was designed with discrete-event simulation in mind.

Relationship between PrimeSupplier, PrimeMap and RSC*Model*

General

The Lead Non-Profit Organization is developing a tool designated as RSC*Model* which is aimed at minimizing the financial impact of both fluctuations in demand and supplier disruptions in a supply chain. The primary contribution of PrimeMap would appear to be in identifying supplier relationships, which aids in identifying critical suppliers and suppliers at risk. PrimeSupplier actually quantifies the risk of a supplier by providing a Total Risk value for each supplier. Additionally, it provides a stability index factor for each supplier which is a supplier health indicator for assessing not only risk, but also how well a supplier may be able to respond to a surge or, more particularly, a sag in demand.

Comparison of Inputs and Outputs

PrimeMap inputs mainly involve supplier location and interrelationship data, as well as live data feeds regarding disasters and associated risks. PrimeSupplier is essentially a "stability index" model, where inputs involve risk factors associated with economic and other stability risks based on financial, operational, and supply chain metrics. Based on this information PrimeSupplier provides a Total Risk value on a scale from 0-10 based on proprietary algorithms. PrimeMap and PrimeSupplier can help determine where the greatest risk factors are in a supply chain that impact overall risk.

Since RSC*Model* looks at strategies for managing both supplier disruption and demand fluctuation, it uses slightly different inputs for each. For supplier disruption it requires an estimate of the probability and severity of a disruption to the supplier. For demand fluctuation it requires information on supplier health and agility. RSC*Model* takes this supplier disruption and health information and simulates scenarios that measure the financial impact of these conditions on the supply chain.

How RSC*Model* could benefit from PrimeSupplier, PrimeMap

RSC*Model* is designed to look at the impact on performance (service level, cost, etc.) that supplier disruptions, demand forecast fluctuations (surges and sags), and different risk mitigation strategies can have on the supply chain. Since RSC*Model* relies on risk and supplier health information as inputs, it could benefit from the risk and supplier health information provided by PrimeSupplier and PrimeMap. Such information could become increasingly more useful in large, complex supply chains. RSC*Model* could also benefit from the disaster risk identification capability of PrimeMap as an important indicator of where to focus risk mitigation efforts. PrimeSupplier and PrimeMap could also aid in supplier selection decisions in RSC*Model* for risk recovery and agility strategies.

How PrimeSupplier and PrimeMap could benefit from RSC*Model*

PrimeMap and PrimeSupplier are focused primarily on identifying supplier risks. The added simulation capability of RSC*Model* could further augment these tools by predicting the actual effects that could result from a disruption in supply or prolonged strain on supplier capacity. RSC*Model* can help assess and identify appropriate supply chain configuration and coordination decisions that mitigate the effects of supply chain risks while minimizing total supply chain ownership cost.

Future Possible Benefits

In the future, RSC*Model* may look at other supply chain risk factors in addition to supplier failure (e.g., product quality, late delivery, etc.). While PrimeMap and PrimeSupplier focus primarily on identifying supplier disruption risks their functionality could be leveraged to identify and quantify other risks such as transportation and late deliveries that could ultimately be feed into RSC*Model*.

Recommended Next Steps

In follow-up to the initial phone conference and inquiries with *Project Manager*, it may be advantageous to further explore technology integration opportunities between NASA Prime Products and *the Lead Non-Profit Organization*, and how each can leverage the strengths of the other. Specific research questions might include:

- How could the technologies be synergistically related (e.g., PrimeSupplier and PrimeMap for risk identification and assessment, and RSC*Model* for subsequent risk management)?
- How could PrimeSupplier and PrimeMap aid in the identification of cost-effective risk mitigation and agility strategies (e.g. selection of alternate suppliers, etc.)?
- What types of data sharing can the products benefit from?
- How might such data sharing occur?
- Is there a potential industry partner that would be willing to collaborate in an integration proof of concept?
- In the future are there other supply disruption risks that could be identified and assessed with PrimeMap and PrimeSupplier that may be worth simulating at an operational level using RSC*Model*?

Appendix: Follow-up Questions and Answers from *Project Manager*

1) **It is our understanding that PrimeMap is capable of exporting supplier data to XLS and PDF formats, is this correct and is there any support for automating data extraction from PrimeMap?**
Yes, PrimeMap is capable of exporting data to XLS and PDF. Regarding automated data extraction, it has the capability but currently there is no automation to "extract" into XLS or PDF.

2) **From information we found on the web (e.g., http://fuentek.net/technologies/Primesupplier.htm), PrimeSupplier produces a single "Economic Stability Indicator" value for each supplier. Is this the same as the "Total Risk" factor you showed us?**
The link you observed is PrimeSupplier v1.0; since then we have been in further development and have a v2.0 which the total risk factor now includes supply chain readiness level (SCRL) and is a stability index.

3) **Besides Total Risk for each supplier, does PrimeSupplier provide any other output data?**
We would like to include a "war game" simulation capability in order to optimize and configure the supply chain, this would include a simulation of procurement dates and other programmatic decisions. This war gaming and overall simulation capability would also relieve potential liabilities in that it would be the customer adjusting and simulating to potential events and planning and is not a static "risk."

4) **Both PrimeMap and PrimeSupplier appear to be web applications, is that correct?**
PrimeMap is a web application, PrimeSupplier is internal however we are in the process of linking PrimeSupplier into PrimeMap, whereas the performance tab on PrimeMap would be the PrimeSupplier risk reference. The Map would be the primary visual/anchor.

5) **What data, if any, is fed from PrimeMap to PrimeSupplier and vice versa?**
Ref Q#4

6) **It is our understanding that neither PrimeMap nor PrimeSupplier currently includes any simulation capability. Is that correct and, if so, have they ever been used with any third-party simulation tools?**

PrimeSupplier v2.0 is designed with simulation in mind (Discrete Event). Regarding 3rd Party, it's been discussed but nothing definite.

Other:
We are currently seeking one final round of funding to complete other external links with PrimeSupplier. Should this final round of funding come through we will have a powerhouse of an application within the next 12 months.

Thank you for your interest in this activity. The applications we discussed would be critical tools in assisting Innovative Industrial Mfg Cluster development, product demand aggregation, agile manufacturing, process commonality and ultimately supporting a free market stimulate for SME [small and medium sized enterprise] growth.

APPENDIX E RSC*MODEL* REPORT AND DOCUMENTATION

E.1 RSC*Model* Functional Specification – Key Points

From the RSC*Model* model development functional specification document, key functional requirements for the prototype include the following:

- A visual representation of the supplier network(s) being evaluated
- Pre-defined performance reports
- No special training or modeling skills needed to use the tool
- An intuitive interface for user input
- Reusable tool for future analysis

E.2 RSC*Model* Operating Assumptions

From the RSC*Model* model development functional specification document, hard-coded assumptions on which the model is based include the following:

- No transportation time
- Risk data is consistent (i.e. not seasonal or periodic) for the duration of the simulation horizon
- Output from a supplier is immediately available for next link
- Existing supply chain is already in steady state production
- The supply chain will not exceed 12 suppliers

- Only 16 suppliers can be defined in the model per scenario
- Each supplier node has a maximum of three subcomponents
- Unknown sub-tier suppliers may exist in the supply chain
- The supply chain data will be known by the customer
- This analysis is particular for a part not an entire system
- This effort is meant to be proactive - prior to a disruption occurring
- When a supplier is removed from the supply chain all change conditions are immediate
- Supply chain will be restored when the same service level rate prior to the disruption is attained

E.3 RSC*Model* – Product Summary and Integration Report

Revised May 17, 2011 *(Revised 1 November 2011 for thesis)*
Authors: B.J. Saunders, Charley Harrell, Jordan Ellingson

RSC*Model* Product Summary

Product Name(s): *Risk Supply Chain Model* (RSC*Model*)
Contact: *Project Lead, Lead Non-Profit Organization*; *Non-profit Participant, Lead Non-Profit Organization*; Bruce Gladwin, ProModel Corp.; Jim Rodgers, ProModel Corp.; Charles Harrell, Brigham Young University

Introduction

This report summarizes the *RSC*Model (*Risk Supply Chain Model*) tool being developed for *a sponsoring government agency*.

Questions and Answers

Below is a summary of answers to typical questions that may be asked about the RSC*Model* tool. Answers are based on information available during development of the tool such as functional specifications and other reports.

1. **How is this tool intended/designed to be accessed? (stand-alone, client-server, Software as a Service, etc.)**
   RSC*Model* is built on a product called ProModel, a commercially available discrete-event simulation software product produced by ProModel Corp. The RSC*Model* product also integrates with Microsoft Office Excel to create a familiar and user-friendly interface for data input and model operation. ProModel and Microsoft Office Excel are both windows desktop applications that typically run as local, stand-alone applications. RSC*Model*, at least for this prototype, is intended to be accessed via a local "runtime" version that doesn't require a full commercial software license.

2. **What is the current state of development of the product? (official release, in alpha or beta testing, in development, etc.)**
   RSC*Model* is currently only a working prototype designed as a proof of concept application for analyzing and optimizing two different, though related, supply chain management challenges: agility and disruption risk. The capability to address these two challenges has been packaged into a single product with a user-friendly interface that allows the user to run surge/sag scenarios, supply disruption risk scenarios, or a combination of the two.

3. **What supply-chain performance issues does the RSC*Model* tool assess? (economic, natural disaster, etc.)**
   RSC*Model* is designed to be a "predictive analytic tool" used to assess the impact of demand fluctuation and supplier disruption on supply chain performance. The analytical and optimization

capabilities of RSC*Model* help program or supply chain managers determine the most cost-effective way to manage supply chain agility and risk.

In analyzing supply chain agility, RSC*Model* uses discrete-event simulation to assess the responsiveness of a supply chain to a surge or sag in demand. A supplier's response to a fluctuation in demand (i.e. supplier agility) is a function of the supplier's capacity (in the case of a surge) and the supplier's health (in the case of a sag). Different supply chain agility management strategies can be evaluated for different demand fluctuation scenarios. RSC*Model* can also automatically identify the optimum (i.e. the most cost effective) supply chain agility management strategy.

In analyzing supply chain risk, RSC*Model* uses discrete-event simulation to assess the ability of a supply chain to handle a disruption in supply. It is an assessment of supply chain resiliency. Risk factors causing disruption may include any event (political, economic, natural disaster, etc.) that could either temporarily or permanently shut off supply from a supplier. Thus RSC*Model* looks at the probability and severity of any such event. Like the analysis for agility, different supply chain risk management strategies can be evaluated for given supplier disruption probabilities and severities. RSC*Model* can also automatically identify the optimum (i.e. the most cost effective) supply chain risk management strategy.

4. **How are supplier agility and disruption risk measured? (ranking, scale, etc.)**
   For supply chain agility analysis, supplier agility is measured in terms of the minimum and maximum production capability that a supplier can sustain. These are expressed in the RSC*Model* tool as percentages of baseline production levels and are determined through supplier surveys.

   For supply chain disruption risk, the risk factors responsible for supply disruption are not expressly stated. Instead, the RSC*Model* tool simply accepts a probability of supplier failure during a specified time frame and a user defined severity for the disruption (duration and cost impacts) in order to evaluate the resultant impact on supply chain performance. Disruption durations can be either temporary or permanent. For the current prototype RSC*Model* tool it is expected that the probability and severity of expected disruptions are determined outside of the RSC*Model* tool.

5. **What output metrics are provided and how is this data interpreted?**

   RSC*Model* provides two ways to simulate and assess alternative strategies for managing demand fluctuation and risk of supplier disruption in supply chains. Up to three different demand fluctuation patterns, disruption risks, and/or management strategies can be evaluated in various combinations (scenarios) through either "analysis" or "optimization." Analysis provides the ability to individually assess scenario performance and is designed to be used when there is a defined strategy the user wants to evaluate. Optimization is achieved by automatically running all possible scenarios to determine which is best. With regards to both objectives, the primary output metric provided by the tool is supply chain Total Ownership Cost (TOC), which takes into account all of the costs and savings associated with a particular supply chain management strategy and risk and/or demand scenario. The principal optimization objective is to identify the management strategy that minimizes TOC.

In either analysis, RSC*Model* provides a set of additional output metrics through summary statistics and time plots that demonstrate behavior over time.

Summary statistics include:

- Total Cost of Ownership
- Total production by supplier
- Average service level
- Average cost per unit

Time plots include:

- Supplier inventory levels
- Supplier production rates
- Cumulative demand
- Cumulative supplier production
- Supplier delivery delay
- Supplier service level
- Cost per unit

An event log for the simulation is also provided. As a side benefit, RSC*Model* also provides a visual schematic of the supply chain based on the configuration data entered by the user. Additionally, through ProModel's Output Viewer customized reports and graphs can be obtained using built in variable tracking in the model.

RSC*Model* gives the user the capability to define real-world variability in the model using probability distributions (though this capability is currently disabled when doing agility analysis). This allows output estimates to be given with confidence intervals.

6. **In what ways can RSC*Model* inputs and outputs be accessed (database, Excel, through an API, etc.), and is there good documentation on this?**
   RSC*Model* input data is entered into an Excel workbook. The output of RSC*Model* is also exportable to Excel. This makes the input and output data easily transportable to and from other applications. The format of this data is defined in the RSC*Model* input and output documentation.

7. **What data must be input into the tool to get meaningful output? (supplier location, years in business, etc.)**
   The RSC*Model* tool is designed for the supply chain (SC) manager or program manager (PM) to input several types of information. Most of the input data is common to both agility and disruption risk analysis functionality. This information includes basic supplier information, demand data for baseline purchase order patterns, supplier production capacities, etc., as well as sourcing cost data such as unit price and other business costs. The user must also create various named datasets from input data to create up to three named scenarios for analysis, select the analysis type (Agility or Disruption Risk), and select the scenario evaluation type (analyze or optimize).

For agility analysis and optimization, additional information is needed including demand pattern, supplier production variance tolerance, and unit price adjustments. For this proof of concept version, only a single tier can be defined for agility modeling.

For risk analysis and optimization, data is entered defining the probability of a supplier being disrupted within a specified time period and the severity of the disruption in terms of duration and cost. The cause of supplier disruption, though not an explicit input, can be due to any real world phenomenon such as the following:

- Natural Disasters
- Financial failure
- Conflict
- Labor issues
- Transportation issues
- Technology failure
- Materials shortage
- Contractual issues

Risk disruption analysis also requires information concerning the current and planned supply chain network configurations including supplier relationships and upstream ordering cycles. The user must also prepare supplier disruption recovery strategies for evaluation in scenarios by determining inventory levels, sourcing cycles, retainer capacity, etc.

8. **What form must this data be in, what is the typical source, and how is it entered? (manual entry, link to database, API, etc.)**

Required input data for supply chain analysis using the RSC*Model* tool comes from buyer and supplier surveys, expertise and experience of the supply chain or program manager, and from other unspecified sources. Demand data may, for example, come from an ERP system and supply disruption risk data may come from risk identification tools such as ___'s RANGER or NASA's PrimeMap/PrimeSupplier.

Microsoft Office Excel is used as the primary user interface and provides ease of data entry through a familiar, user-friendly, and widely accepted standard spreadsheet application. In its current state, RSC*Model* relies on manual entry of input data across several logically sequenced Excel tabs/worksheets. The use of Excel for data input provides a wide range of possibilities for future data entry methods through databases, etc. In addition, ProModel (the simulation software used for RSC*Model*) has a diverse group of user interface options, capable of implementing data connections with other applications, which can be considered for future development and application of the RSC*Model* tool.

9. **Who is currently using this tool and what has been the response?**

RSC*Model* has been developed as a proof of concept modeling tool using a real-world industry test case. The tool is being built and tested in cooperation with industry partners for analysis of a specific sub-component supply chain, although the tool is designed to be applicable for future analysis of other supply chains. The intent is for RSC*Model* to be usable by a supply chain (SC) manager or program manager (PM) with knowledge and access to information about the supply chain to be analyzed. Evaluation of the tool and its use is ongoing.

10. **What significant future enhancements are planned for RSC*Model*?**
Currently, stochastic modeling is enabled only when doing risk analysis. The ability to incorporate Monte Carlo type simulation will eventually be extended to agility analysis modeling as well. The supply disruption risk is currently focused primarily on the risk of supplier disruption; however, future enhancements may make analysis of other risk factors possible. Currently, RSC*Model* runs as a stand-alone application. Future work will look at integrating RSC*Model* with other DOD supply chain applications. Since RSC*Model* was initially developed as a proof of concept, it is limited as to the size and complexity of supply chain it can work with. The architecture, however, is designed to support supply chains of virtually any size and complexity and this will be tested in the future.

11. **What further development/customization of the GUI or deeper program elements would be needed to make it useful for other uses outside of DOD applications?**
The RSC*Model* tool uses a nodal design approach that provides the groundwork to allow for simple future scalability and ease and flexibility in supply chain configuration and reconfiguration. With the enhancements defined above, it should be well suited for making supply chain agility and risk management decisions in industries outside of the DOD.

RSC*Model* Strengths and Weaknesses

Product Strengths

- Presents a visual representation of the supplier network(s) being evaluated.
- Performance reporting is visual and easily understood and reports can easily be saved for later reference.
- Offers an intuitive user interface using Microsoft Office Excel and requires no special training or modeling skills.
- The modeling framework is scalable and reusable providing for flexibility in future use of the tool
- Provides the ability to assess the *impact on performance* (service level, cost, etc.) that supply disruptions, demand fluctuations (surges <u>and</u> sags), and different risk mitigation strategies can have on the supply chain.
- Provides the ability to dynamically assess the cost-effectiveness of supply chain management strategies for dealing with supply disruptions and demand fluctuations.
- Product platforms provide for ease of future data feeds and links.

Product Weaknesses

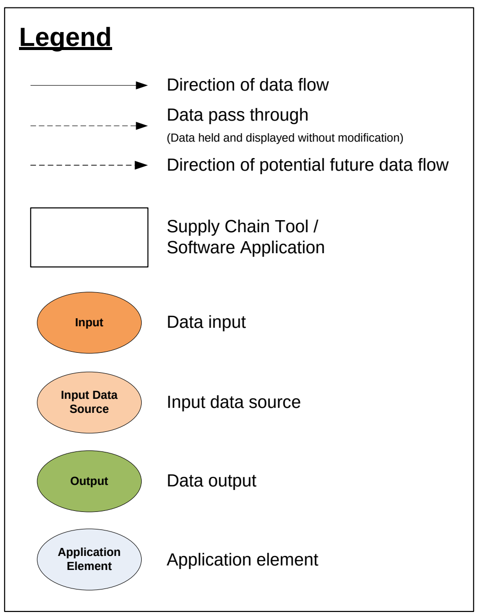
- RSC*Model* has no systematic method of identifying the factors that contribute to supply interruptions.
- RSC*Model* has no reliable method of quantifying the probability or severity associated with a disruption, but instead relies on other tools and methods for supply disruption risk identification.

Recommended Next Steps

- Find opportunities for implementation within the DoD that will take the product from a prototype into full production tool.
- Establish integration opportunities with Ranger and Prime Map/Supplier.

APPENDIX F SUPPLY CHAIN TOOLS – INPUT/OUTPUT DIAGRAMS

F.1 Input/Output Diagrams Legend



As part of the effort to assess the integration potential and complementary capabilities of *the Risk Supply Chain Model* (RSC*Model*) tool with other government-funded supply chain modeling tools (RANGER, PrimeSupplier, and PrimeMap), the following diagrams identify the input and output information of each tool. A conceptual diagram helps identify which tools are outputting information that could serve as inputs to others, especially to SCR*Model*.

Authors: B.J. Saunders
Charley Harrell
Jordan Ellingson

DESCRIPTION	DATE
Legend for Input / Output Supply Chain Tool Diagrams	6/9/2011

Figure F.1 – Input/Output Diagrams Legend
(Revised 16 November 2011 for thesis)

F.2 RANGER I/O Diagram

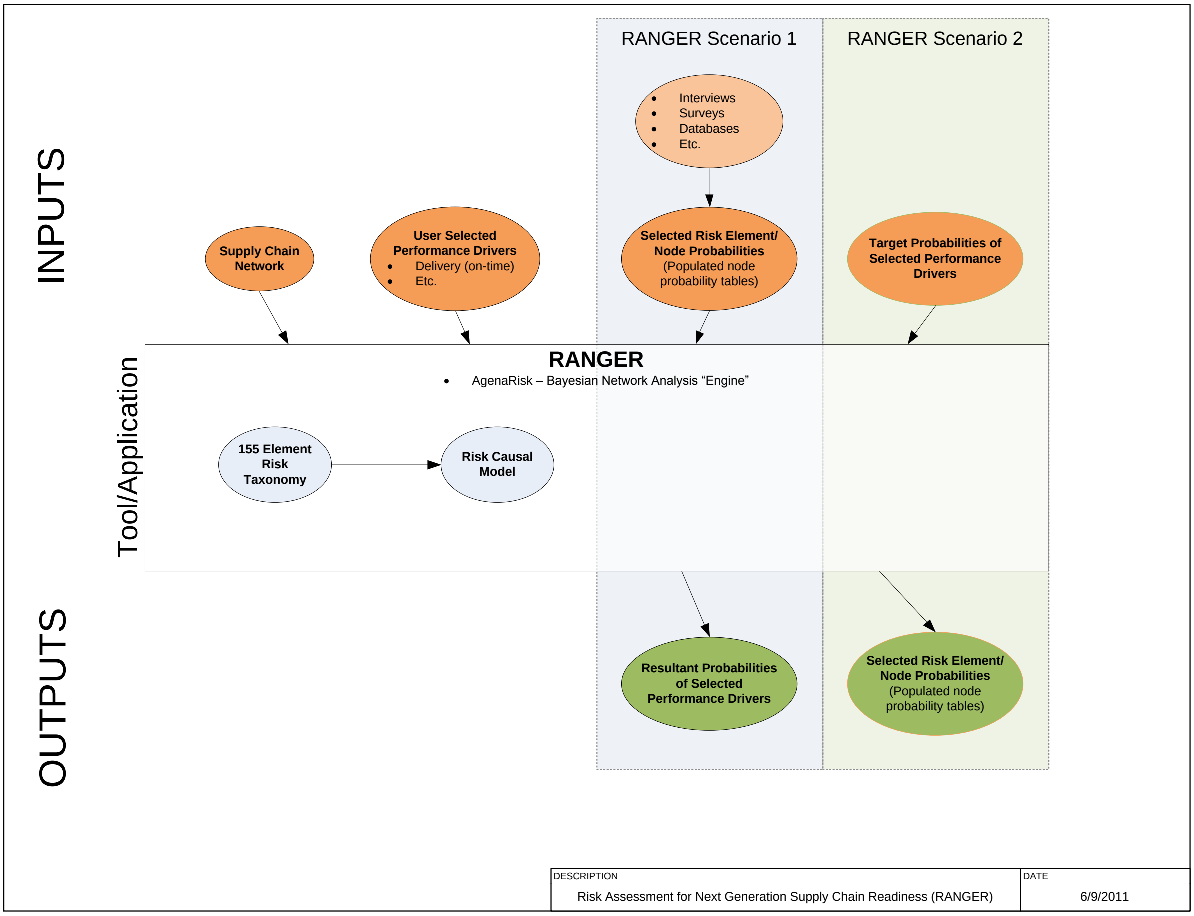


Figure F.2 – Ranger I/O Diagram

F.3 PrimeMap I/O Diagram

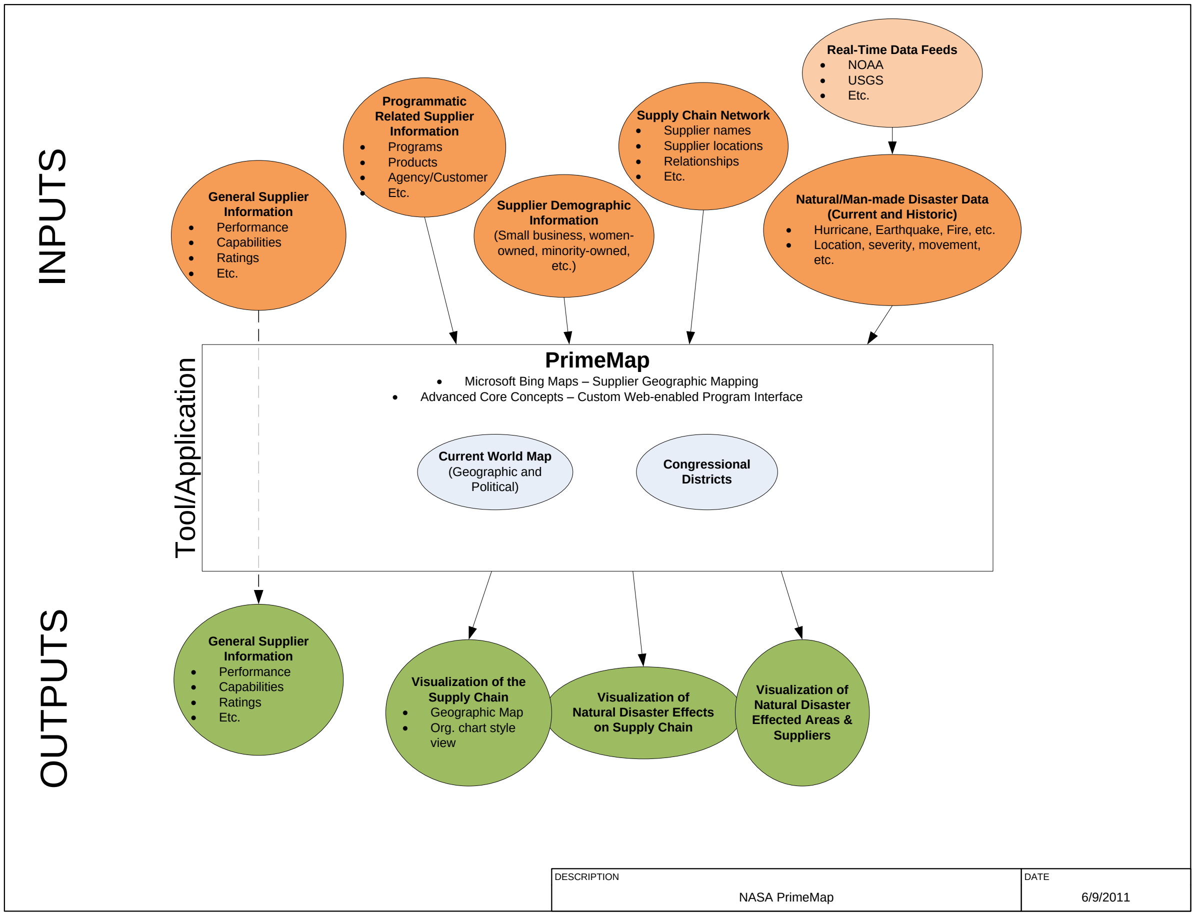


Figure F.3 – PrimeMap I/O Diagram

F.4 PrimeSupplier I/O Diagram

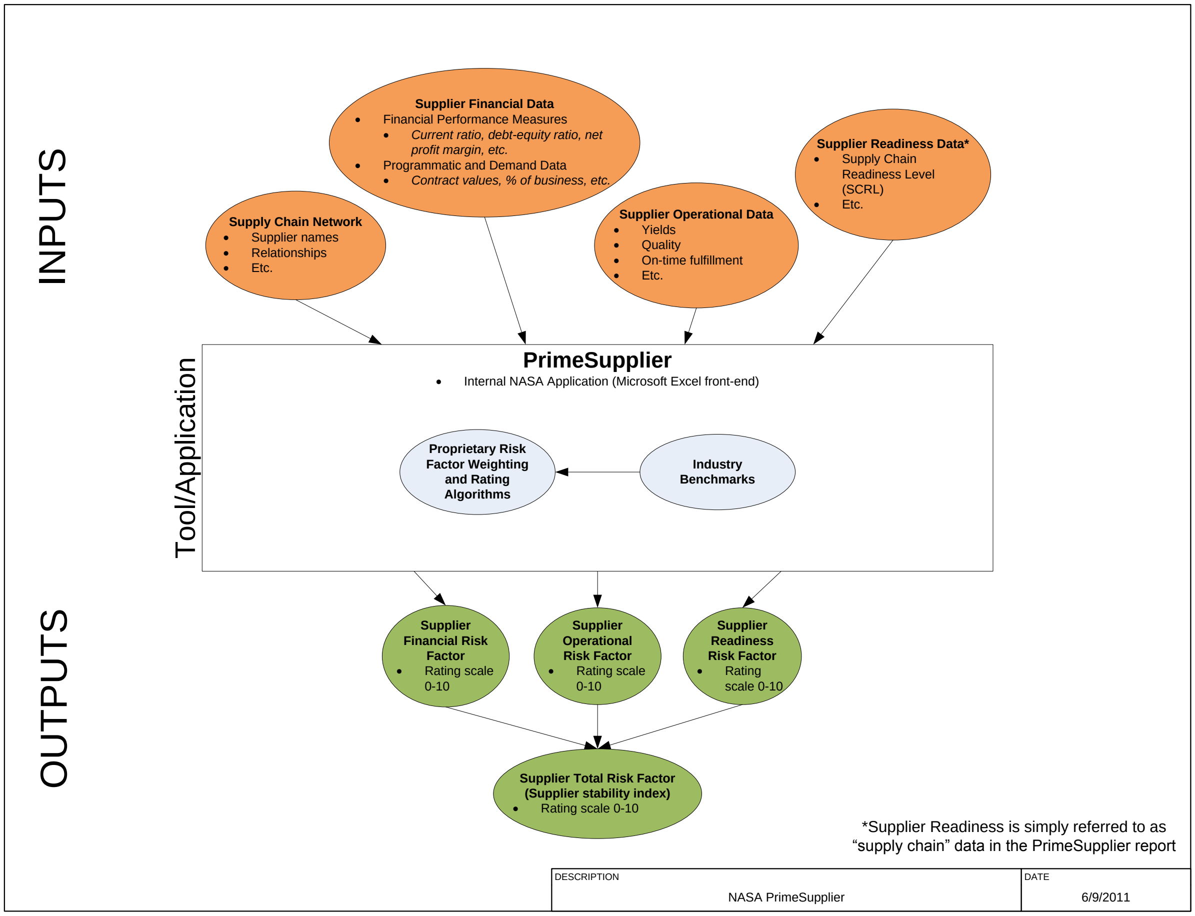


Figure F.4 – PrimeSupplier I/O Diagram

F.5 Prime Products Link Diagram

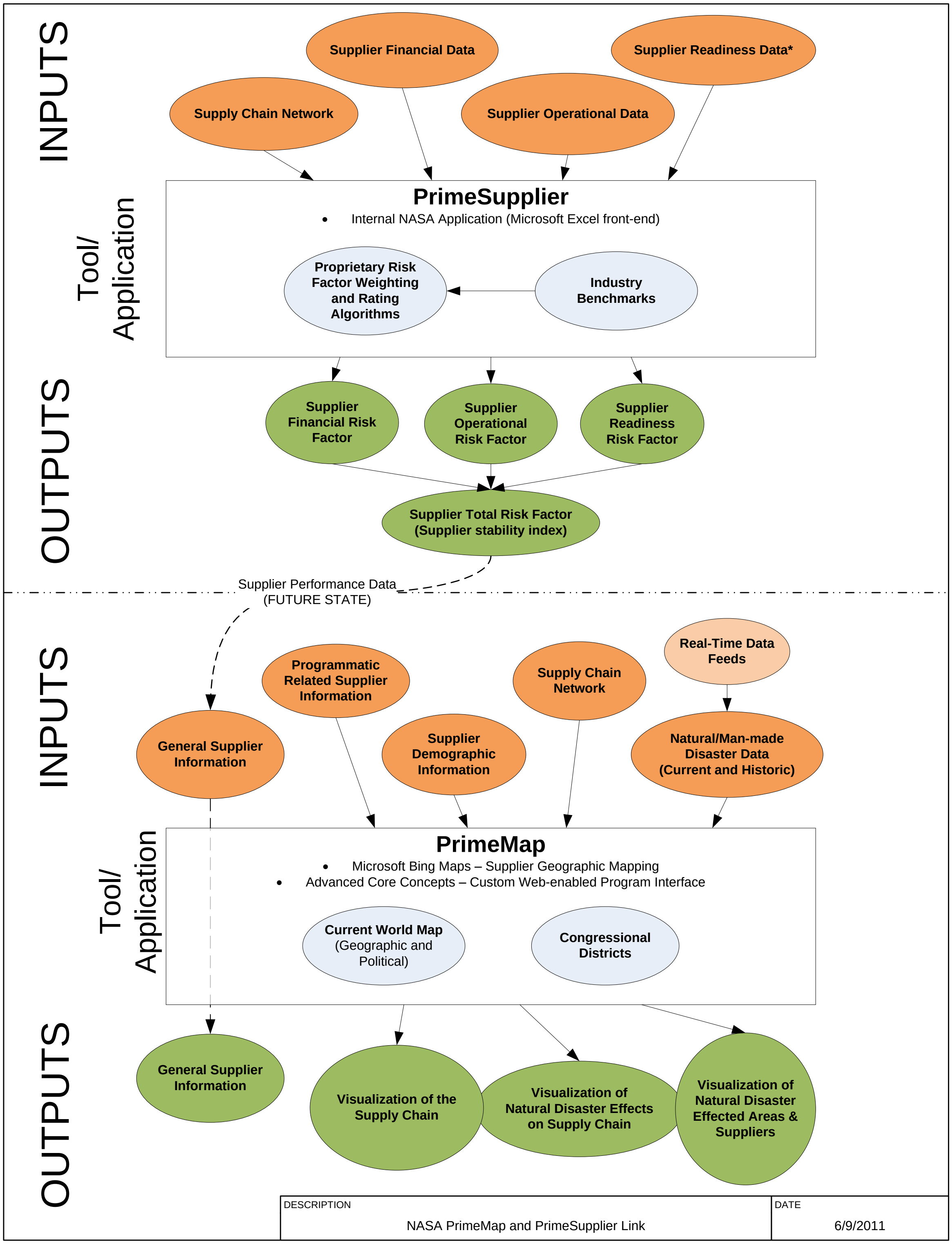


Figure F.5 – Prime Products Link Diagram

F.6 RSC*Model* I/O Diagram

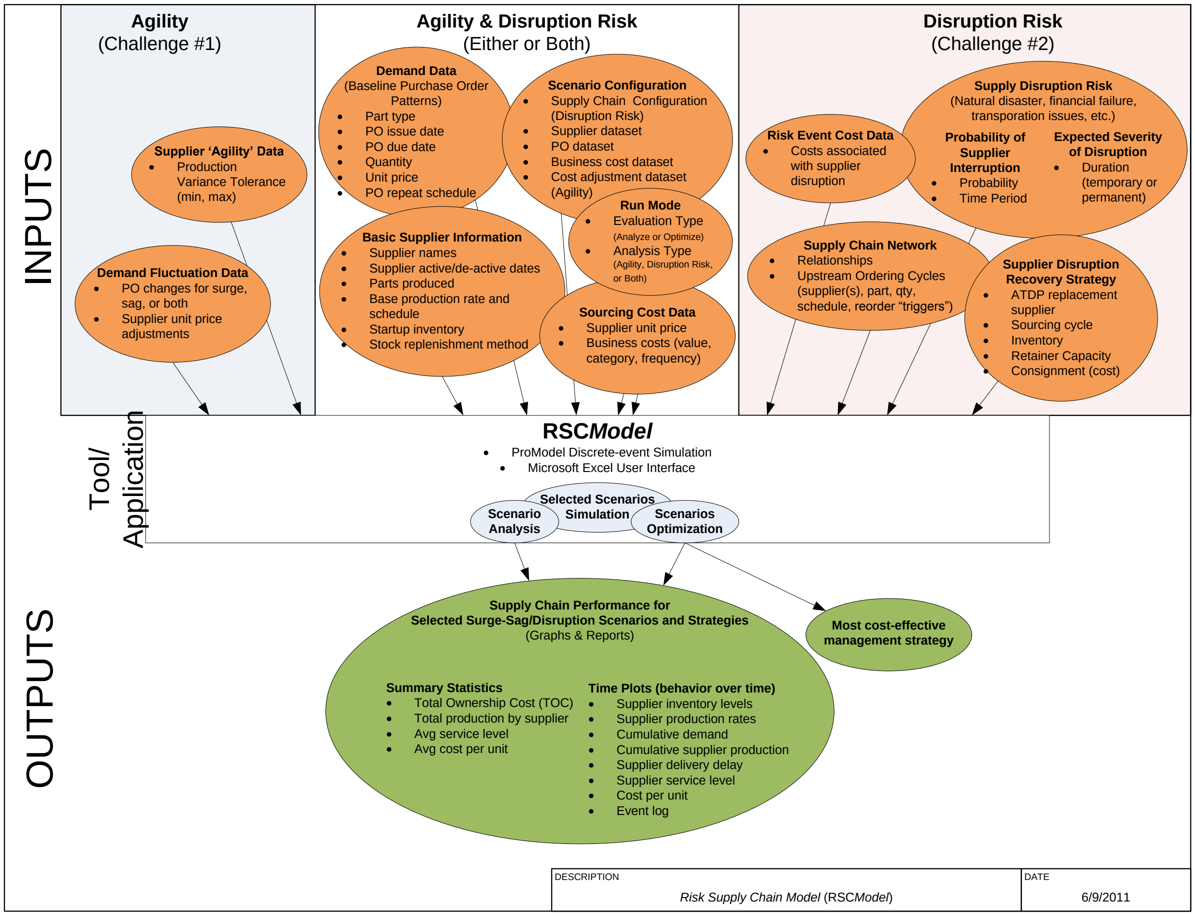


Figure F.6 – RSC*Model* I/O Diagram
(Revised 16 November 2011 for thesis)

F.7 Conceptual Tool Integration Diagram

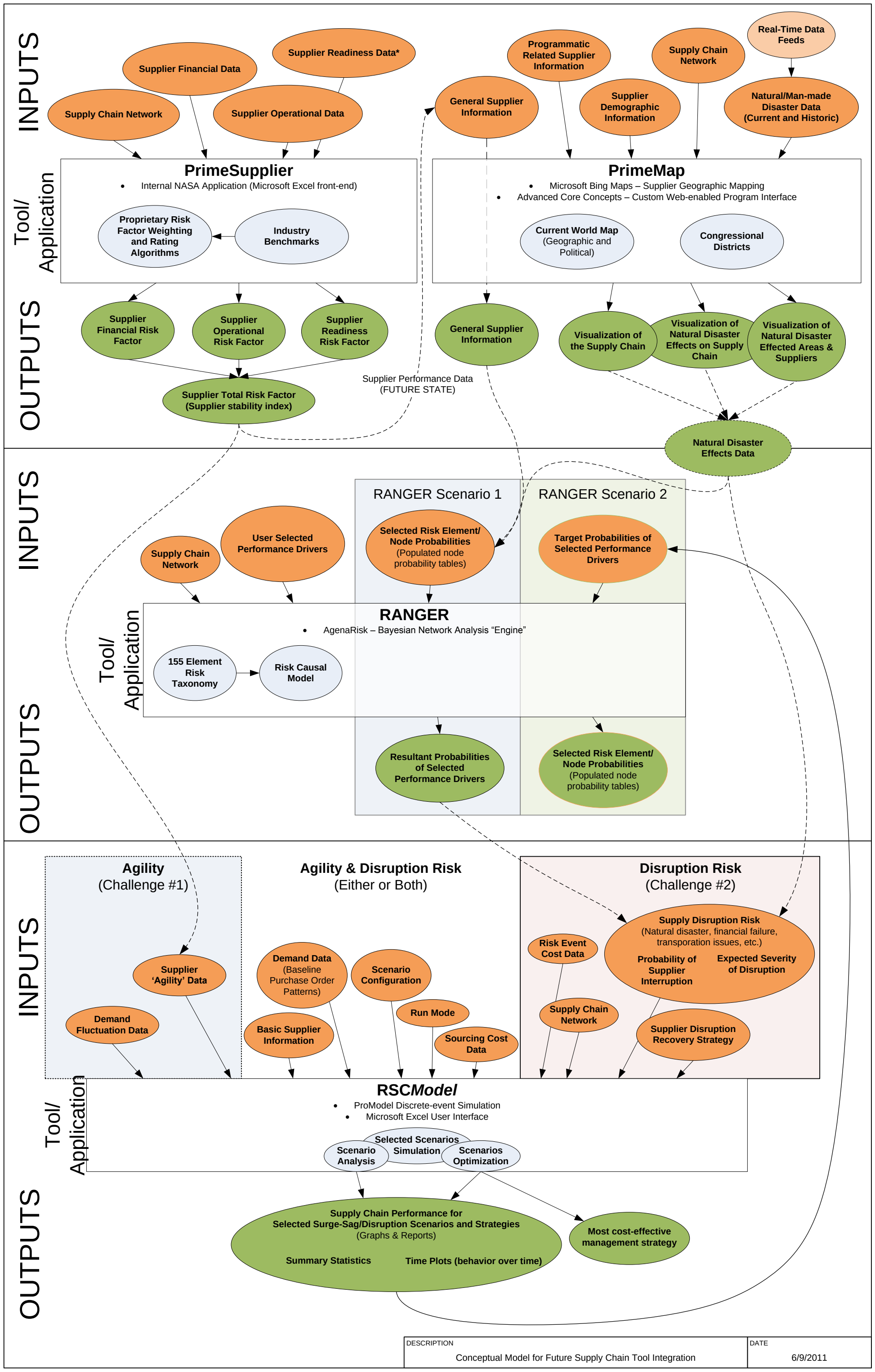


Figure F.7 – Conceptual Tool Integration Diagram
(Revised 16 November 2011 for thesis)

F.8 Simplified Tool Integration Diagram

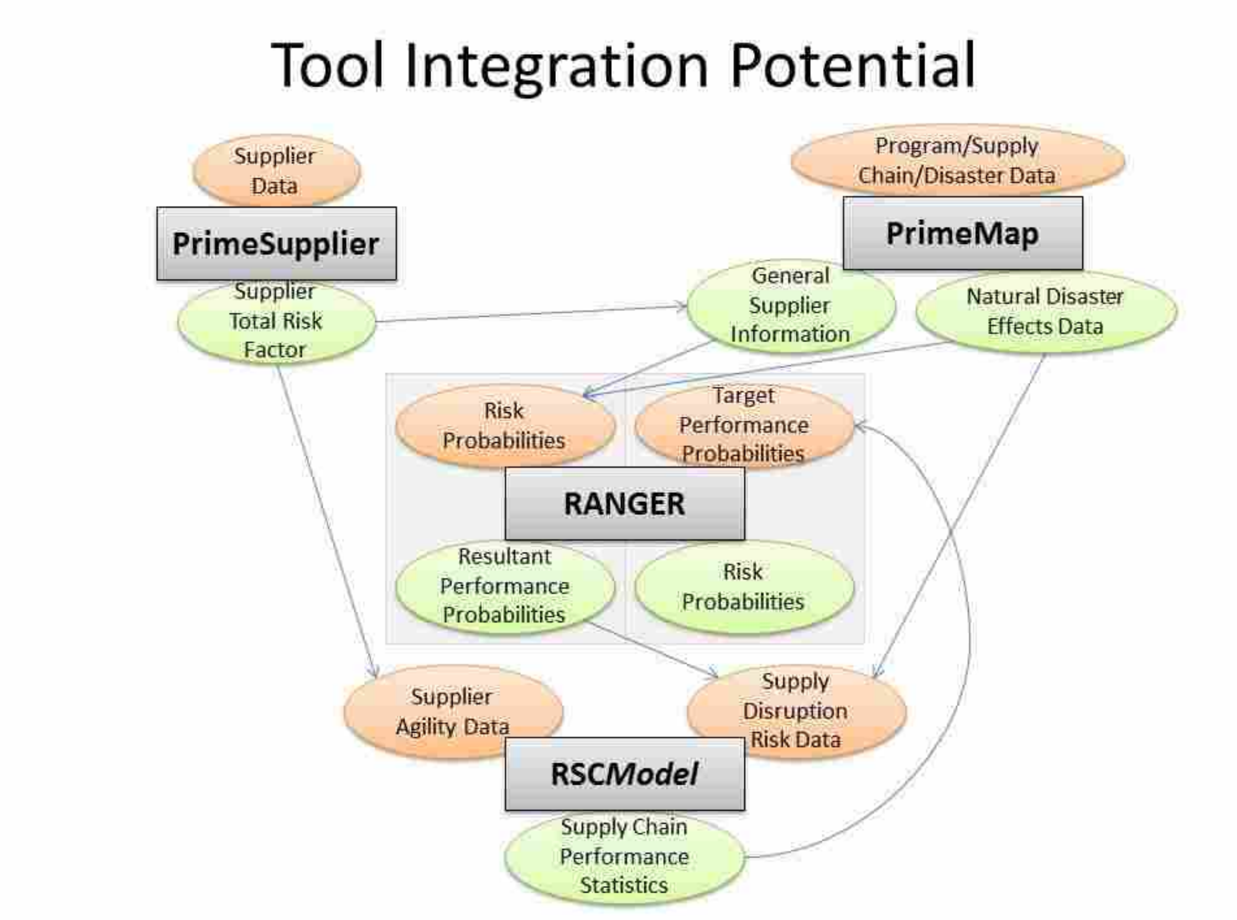


Figure F.8 – Simplified Tool Integration Diagram
(Revised 16 November 2011 for thesis)