A Supply Network Resiliency Assessment Framework

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ABSTRACT

Supply chain resiliency is a relatively new field within supply chain management. Many quantitative and qualitative resiliency frameworks are available. However, there is a need for a hybrid framework that provides a more comprehensive resiliency assessment. In this thesis, we attempt to synthesize important features from different assessment frameworks and develop a hybrid resiliency assessment framework that more comprehensively addresses resiliency assessment. Our proposed framework combines quantitative assessment with a qualitative assessment to create a single Balanced Scorecard of Resiliency (BSR).

We deployed the quantitative assessment of the BSR framework in a single commodity supply chain of ABC Company, and were able to compute the expected business impact risk of each node. We also aggregated across multiple nodes to assess the expected business impacts of each of the facilities, suppliers and locations of ABC Company's supply chain, and identify the critical entities in the supply chain for mitigation planning. For the critical facilities, suppliers, and locations, we developed response curves of the expected business impact for key parameters to identify the best mitigation options and the extent of investments. Lastly, we used a supply chain visualization tool called Sourcemap to visualize the expected business impact risk in both a map view and supply network view. Our quantitative assessment of resiliency allowed us to gain insights and generate recommendations for improving ABC Company's supply chain resiliency.

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1. INTRODUCTION

Supply chain resiliency is a relatively new field within supply chain management. However, as companies are getting more global, supply chain resiliency is gaining more visibility due to the negative impacts that disruptions can cause to a company's ability to compete.

The effects that disruptions (and their aftershock) have on supply chains are far from inconsequential. For instance, in 2011, the floods in Thailand caused billions of dollars in damage to major companies around the world. During the same year, the earthquake and tsunami in Japan had an astronomical impact on companies around the world ("Japan after the tsunami: Grinding on," 2015). The companies that were best able to deal with the disruption triumphed as leaders in the market. The best way to prepare for disruptions is to assess the resiliency of the supply chain and have risk mitigation plans in place. However, since supply chain resiliency is a relatively new field, we believe that the available supply chain resiliency assessment frameworks are inadequate.

Traditionally, supply chain managers manage supply chain resiliency based on gut feel and intuition. For example, in the auto industry, most of the risk management is focused on high dollar, high volume suppliers. However, in many cases, the riskiest supply chain nodes could be a minor supplier. Therefore, a resiliency assessment framework is needed to analyze the supply network holistically and quantitatively.

Many quantitative and qualitative resiliency frameworks such as Risk Exposure Index (REI) and Value-At-Risk (VAR), etc. are available. However, no single framework addresses all the important issues for conducting a comprehensive resiliency assessment. The lack of a silver bullet framework requires us to consider creating a new framework without the same weakness. Therefore, we synthesized important features from various assessment frameworks and developed a hybrid resiliency assessment framework that more comprehensively addresses resiliency assessment. We call this new assessment framework the Balanced Scorecard of Resiliency (BSR). The BSR approach combines quantitative assessment methods with qualitative characteristics to create a single hybrid risk score.

To validate our BSR assessment framework concept, we applied the BSR assessment to one commodity of ABC Company. ABC Company is high technology company with suppliers throughout China and Taiwan. Due to limited project scope, we focused on the quantitative assessment of one commodity in the upstream supply chain to find the expected business impact dollars. The qualitative assessment will be part of a later study. Our BSR assessment identified a total expected business impact risk of $2,968K USD for the one commodity of ABC Company. We visualized the business impact risk exposure through a map view and supply network view for ABC Company using a visualization tool called SourceMap.

In this thesis, we will first provide a literature review that details different quantitative and qualitative resiliency assessment methods. We will then describe how we arrived at our BSR assessment framework and how we applied our methodology. Next we will analyze the methods that were effective and not effective and how we arrived at our final results. Then we will summarize our findings to show the impact of our BSR resiliency assessment framework.

2. LITERATURE REVIEW

2.1 Background and Scope

Resiliency is the ability of a system to bounce back from a disruption (Fiksel, 2006). Many articles have been written on the topic of methods to assess resiliency in a supply chain. Many of these methods include either a quantitative or qualitative assessment. In the following sections, we will present the broad themes in literature on the topic of assessing supply chain resiliency, highlight the strengths and weaknesses of particular approaches, and propose a framework for a comprehensive assessment for optimizing supply chain resiliency.

2.2 Types of Vulnerabilities

Before planning a resiliency assessment, it is useful to identify and understand the sources of vulnerabilities. Pettit, Croxton, & Cooper provides an exhaustive list of seven different types of supply chain vulnerabilities: turbulence, deliberate threats, external pressures, resource limits, sensitivity, connectivity and supplier/customer disruptions (Pettit, Croxton, & Cooper, 2010). These vulnerabilities range from natural disasters to limitations of suppliers to other external economic factors that impact supply chains. This vulnerability list allows us to map the potential sources of threats and assign a probability associated with the risk when performing a quantitative resiliency assessment on a supply chain.

2.3 Quantitative Resiliency Assessment

A quantitative resiliency assessment measures or assesses the resilience of the supply chain in objective, quantitative measure. For example, quantitative measures can include how fast a system can respond, the cost to mitigate a risk, the cost to recover, and the anticipated financial impact on the business. The challenge of measuring resiliency is that a single numeric index would need to be defined to objectively measure the risk exposure of a firm throughout its supply chain. The numeric index would also need to be complex enough to cover the different capabilities and financial measures of a node. The supply chain nodes that have the highest values are then identified for resiliency investments as part of resilience planning. There are many variations of quantitative resiliency assessments and most of them start by defining a numeric index to assign to the nodes, then assigning a risk score that combines probability and business impact.

2.3.1 Generating a numeric risk score

Quantitative supply chain resiliency assessments often focus on generating a single numeric risk score for each node in the supply chain. The nodes are then ranked according to the risk scores and the highest ranked nodes are targeted for improved resiliency planning. Different approaches advocated by different authors provide variations on how such a risk score is computed (Sheffi, 2015). The dominant approach to computing such a risk score is to generate the probability of a potentially adverse impact event or disruption at the node, and combine it with the potential business value impacted, to create a value-at-risk (VAR) metric. The literature differs on how the probability of the risk event is computed, how the potential business value impacted is computed, and how these two are combined.

2.3.2 Defining a probability of a disruptive event

Two main approaches are commonly used to generate the probability of a disruptive event. Since there is no objective way to assess the probability of low-probability events, the dominant approach identified in the literature is to define risk categories and invite subjective inputs from managers on the risk levels of each node on each category, and to synthesize a final probability of disruption (Lockamy, 2011). The other approach is use third party companies that aggregate data on various categories of disruptive events; for example, third party AIR Worldwide (AIR) has aggregated data on the probabilities of natural catastrophes in different regions of the world. Probabilities of disruptive events can be retrieved from AIR's database and used for calculations. Once the probability of disruption is generated, we can combine it with the potential business impact to generate a risk score.

2.3.3 Calculating potential business impact value from risk event

One dominant method to calculate the potential business value impact of a supply chain disruption is to use an index of risk exposure. The Risk Exposure Index (REI) is a measure of exposure calculated for all nodes and links in the supply chain (Simchi-Levi, 2014). Its purpose is to reveal the riskiest points/pathways in the supply chain as measured by potential revenue loss. REI is calculated by multiplying the 'revenue enabled by supplier node' times the 'dollar amount of inventory available' and then times the length of time to recovery, also known as time to recovery (TTR).

2.3.4 Combining Probability and Business Impact

Different methods for combining the probability of disruption and the potential business value impacted have been explored in literature. The standard approaches have been matrix categories (Norrman, 2004) and direct multiplication (Arntzen, 2014). Some interesting approaches such as logit models (Jung, 2011), Bayesian networks (Lockamy, 2014) and analytical hierarchical processing (Wu, 2005) have also been tried, but their applicability is restricted due to specialized conditions of data requirements and scalability.

2.3.5 Business Value Impacted

While identifying the potential business value impacted, we noticed a progression in the literature in terms of the increasing scientific rigor of the approaches advocated. Earlier studies such as Norrman (Norrman, 2004) arrive at an impact-level category qualitatively, while more recent ones such as Hi-Viz (Sourcemap, 2014), modified-VAR (Sheffi, 2015), and Dynamic REI (Simchi-Levi, 2015) compute potential business value quantitatively. Both Sheffi and Simchi-Levi provide an additional feature that optimally models the re-planning that occurs after a disruption. Re-planning means how resources are reallocated once a disruption occurs and disrupts a supplier's ability to deliver goods. While Sheffi considers fair allocation of inventory and optimal allocation of the partial rate of supply (the capacity still functioning after disruption) to customers, Simchi Levi considers optimal allocation of both inventory and the partial rate of supply. Generally speaking, quantitative measures of potential business impact are more objective and therefore believed to be more reliable, and we will continue in that vein for this thesis. There are, however, other qualitative resiliency assessments in the literature.

2.4 Qualitative Resiliency Assessment

A qualitative resiliency assessment measures or assesses the resilience of the supply chain in subjective, qualitative measure. The Supply Chain Risk Leadership Council (SCRLC), a cross-industry council world-class product and service companies working together to develop supply chain risk management best practices) has developed an assessment method referred to as the Supply Chain Risk Management Maturity Model. The model assesses a corporation's maturity in five categories: Leadership, Planning, Implementation, Evaluation and Improvement. This assessment sets a benchmark on how to rate a corporation's maturity in supply chain risk management. However, the assessment is based on the subjective opinions of the stakeholders involved in rating. The assessment also does not mention Business Continuity Planning (BCP). BCP is a common tool we have observed in our resilience assessment literature research. BCP is a planning tool that identifies an organization's exposure to internal and external threats and synthesizes hard and soft assets to provide effective prevention and recovery for the organization, while maintaining competitive advantage and value system integrity (Elliot et al. 1999). BCP is also used to ensure business continuity through the development and preparation of backup plans. Both the SCRLC Risk Management Maturity Model assessment and BCP are internal facing and do not consider external facing factors such as the firm's ability to assess its suppliers.

Jung, Lim, & Oh detail a comprehensive framework to assess key suppliers (Jung, Lim, & Oh, 2011). Each supplier is rated in terms of three categories: part-market characteristics, financial variables and operational characteristics. Part-market characteristic refers to the supplier's overall reputation in the market. The financial characteristic extracts key financial indicators from the supplier such as working capital to total assets (WCTA) and earnings before interest and taxes to total assets (EBITTA) etc. to assess the financial conditions of a company. The operational characteristics refer to four main categories: technology, quality, delivery and costs. This supplier assessment framework combined with the SCRLC Risk Management Maturity Model assessment and BCP could give the corporation a detailed internal and external qualitative assessment regarding supply chain resiliency.

2.5 Hybrid Resiliency Assessment

Each of the papers surveyed above focuses on either a quantitative or qualitative approach to assessing supply chain resiliency. However, a hybrid approach that combines strengths of various approaches is better suited for a comprehensive assessment of a complex global supply chain. In the methodology section, we will propose a Balanced Scorecard approach that combines quantitative risk exposure index with important qualitative characteristics to create a single hybrid risk score.

3. METHODOLOGY

The main objective of this thesis is to develop a resiliency assessment framework that could potentially be used to assess multiple facets of resiliency of a supply chain system at multiple levels of the supply chain. In the literature, we found different approaches that each assessed a different facet of resiliency in depth, but an approach that combines different facets of resiliency assessment was missing. Therefore, we propose an approach that combines relevant features, and creates a hybrid assessment framework.

3.1 Hybrid Resiliency Assessment

Each of the approaches surveyed in literature focuses on a single approach to assessing supply chain resiliency. However, a hybrid approach that combines strengths of various approaches is better suited for a fuller assessment of a complex global supply chain. For example, while it is important to assess the risk and resiliency at a given node, it is also useful to assess the parts (Ho, 2009), and the process of assessing (SCRLC, 2006).

Figure 1 shows a summary of the literature we have reviewed. The highest-level categories are "assessment" and "process of assessing." Under "assessments,", different subcategories are nested.

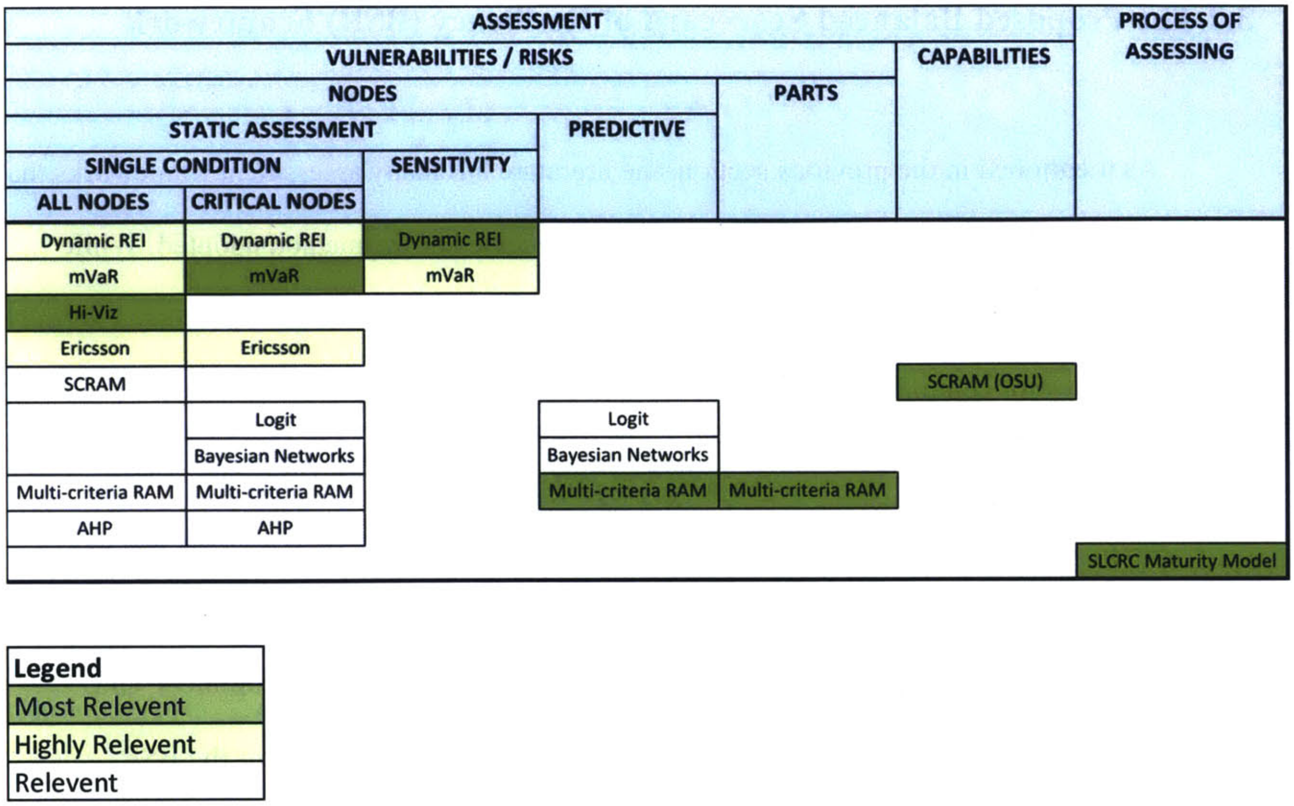

Figure 1 – Building the balanced scorecard of Resiliency

Within each column, the various literatures relevant to the assessment component are listed. Each row shows the same literature and how it relates to the different assessment components. The color-coding indicates how relevant the particular method (row) is to the type of assessment (column), as explained in the legend.

While there are many ways to select and combine the different assessments, we refer to the seminal work by Robert Kapan and David Norton (Robert, Norton, 1996), who combined financial and non-financial performance measures to create a Balanced Scorecard approach in the field of strategy, and propose a similar Balanced Scorecard approach to resiliency assessment that combines a quantitative assessment with a qualitative assessment. We believe that this assessment framework will demonstrate the benefits of using a hybrid approach over a specialized approach.

3.2 The Proposed Balanced Scorecard of Resiliency (BSR) Framework

As mentioned in the previous section, the literature has many assessment frameworks that differ based on the features of the supply chain being assessed or the method adopted. While there were useful features in many different frameworks, no single framework addressed all the important issues for conducting a comprehensive resiliency assessment. To demonstrate the value of a hybrid approach, we combined more than one type of assessment into an overall risk score. We then synthesized important features from various assessment frameworks and added some new features. We developed a simple and intuitive assessment framework that assesses resiliency in the supply chain at multiple levels such as processes, facilities, suppliers, and locations. We call this new framework the Balanced Scorecard of Resiliency or the BSR.

The BSR is a hybrid resiliency assessment framework that combines a quantitative assessment with a qualitative assessment. Figure 2 shows the quantitative and qualitative elements. We believe that it will help managers identify the location and magnitude of risk in the supply chain, and prioritize opportunities for improving resiliency. Secondly, it can also help identify and evaluate alternate courses of action to mitigate risk and improve resiliency. Finally, it provides an assessment of the maturity of the resiliency assessment process as well.

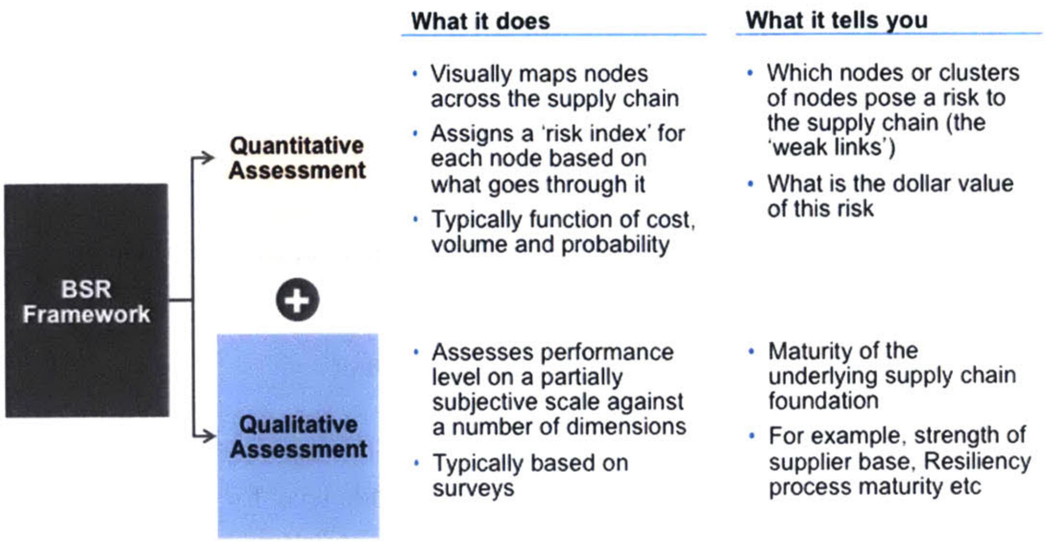

Figure 2 – Quantitative and qualitative elements of BSR framework

For the purposes of testing out our concept, we applied the BSR to the upstream or supply side of a supply chain in a tech company. The results obtained will indicate the potential usefulness of this approach. If found to be useful, we believe that the same assessment methodology can be applied to analyzing downstream distribution as well.

3.2.2 How does the BSR Work?

The Balanced Scorecard of Resiliency (BSR) is a hybrid assessment framework and methodology that aims to help assess the resiliency of the supply chain at multiple levels and meets some of the key objectives of resiliency assessment and improvement in a supply chain system. As illustrated in figure 3, the BSR is a combination of quantitative and qualitative assessments.

BALANCED SCORECARD OF RESILIENCY		
	Level	**Objectives**
Quantitative	Node, Supply Chain	Quantify, prioritize, and mitigate Risk
Qualitative	Supply Network	Evaluate Resiliency Process Maturity

Figure 3 - Main elements of BSR

The quantitative assessments are conducted at the node level for each supply chain within the supply network. The outputs of this assessment (listed and explained in section 3.3) indicate the extent of risk present at a given node of the supply chain. The node-level quantitative outputs can be rolled up to aggregated levels of the supply chain such as entire facilities, locations, and suppliers. This is expected to help prioritize the sets of nodes such as critical processes, facilities, suppliers, locations, and commodities that have the greatest risk, so that managers can focus attention on the most critical sites for resiliency improvement action.

On the other hand, the qualitative assessment is conducted at the level of the entire supply network system. We define the supply network system as the accumulation of all the nodes that make up the entire supply network, and also the processes and relationships that link these nodes. For example, apart from the nodes mentioned in the previous paragraph, which could refer to suppliers or facilities, the supply network also includes relationships such as supplier-customer relations and processes such as order fulfillment process. The qualitative assessment identifies the maturity of the resiliency assessment and process improvement opportunities.

Taken together, the quantitative and qualitative assessments of the BSR have the potential to address the resiliency of the supply chain at multiple levels (node, supply chain, supply network system) and address major assessment objectives such as extent of risk, prioritization of improvement efforts, recommendations to increase resiliency, and status of the resiliency assessment and improvement process in the entire supply network system. Thus, the BSR may be able to provide a more comprehensive picture of the resiliency of a supply chain system.

3.3 Quantitative Assessment of Resiliency:

The quantitative assessment estimates the expected business impact (BI) of a disruption of the supply chain. The disruptions may be at the level of a process, a facility, a location or a supplier. We start by presenting a stylistic timeline to illustrate the process and to define terms.

3.3.1 Stylistic Events Timeline and Definitions

Events Timeline

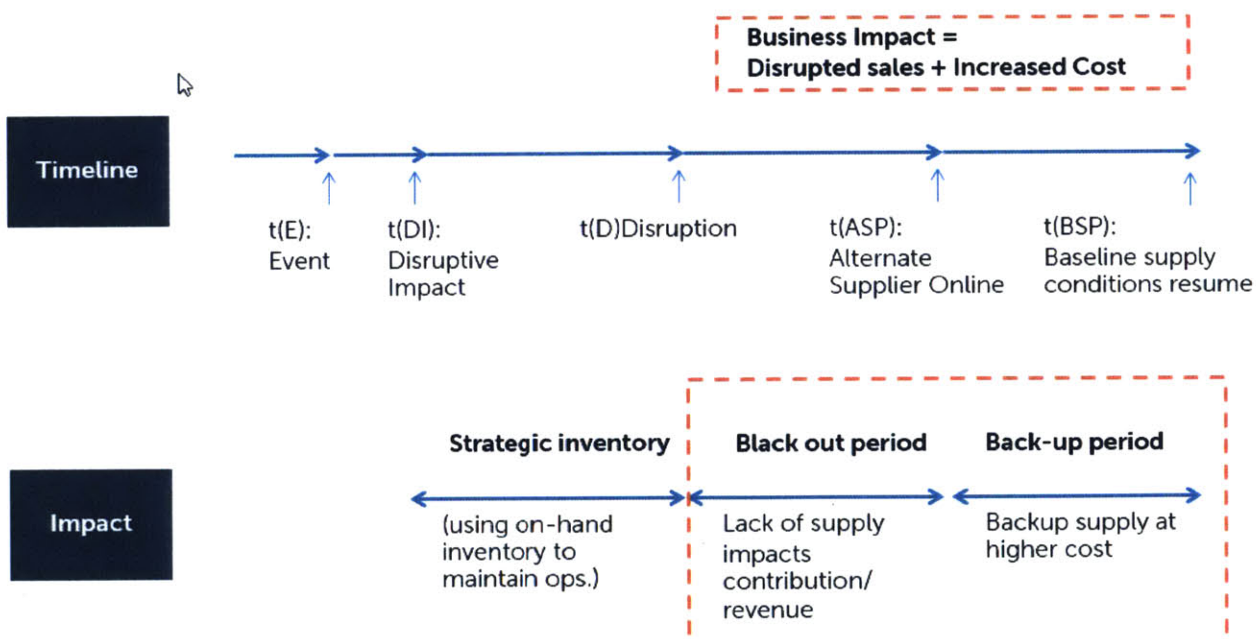

Figure 4 - Time of events and definitions

Definitions:

While there are many possible definitions that may fit, we believe the ones we have chosen below best illustrate the methodology developed in subsequent sections. Since slightly different variations in definitions are possible, we identify some of the important nuances for each term and explain them a bit more in detail,

1. t(E), the time at which an Event occurs:

The resiliency timeline starts with the occurrence of an event that may or may not result in a disruptive impact on a supply chain node or link. The event could have a small magnitude or a large magnitude, with a corresponding probability of occurrence.

a. Major and Minor Events:

The full set of disruptive events is divided into major and minor events. Major events are larger events such as natural disasters that cause a much greater loss of capacity for the node and from which the affected nodes take a longer time to recover. Minor events are smaller events such as process failures that cause a smaller loss of capacity for the node and from which the affected nodes can recover in the relative near term.

b. Probability of Event:

This is the probability of occurrence of the event. The probabilities of major and minor events are different, since the events themselves are different. Major events tend to be external to the supplier, while minor events tend to be internal to the supplier. Therefore the probabilities for major events come from external data sources, while the probabilities for minor events come from internal operational history.

2. t(DI), the time at which the Disruptive Impact occurs:

Prior to the occurrence of the Disruptive Impact, the supply chain is assumed to have been at steady state, both in terms of the output volumes and input costs. In other words, the output volumes and input costs before the Disruptive Impact are considered as the baseline values for the supply chain.

a. Event vs. Disruptive Impact:

Only those events that lead to a loss of productive capacity at a node or a link in the supply chain are considered to have disruptive impacts. For example, an earthquake that occurs in the region is considered an event. But if this event leads to a loss of productive capacity at a node or a link in the supply chain, we consider it to be a disruptive impact as well.

The timing of the two may or may not be the same, depending on the time lag from when the event occurs, denoted by t(E), to when it impacts the supply chain, denoted by t(DI)

b. Partial vs. Full Disruption:

Events with Disruptive Impacts affect the capability of a node or a link in the supply chain. This loss of capability could be either complete or partial.

For our assessment framework, we consider all disruptions to be full disruptions. We model full disruptions by assuming that available inventory is used at full volume while it is available, and at 0% when it is not – as opposed to using the available inventory at less than 100% demand for a longer period of time.

c. Known vs. Unknown:

Sometimes, information about disruptive events, such as a labor strike at a supplier facility, is not shared with the downstream supply chain until much later. During this time, the facility has already lost productive capability, but is meeting downstream demand from strategic inventory. However, the downstream supply chain inaccurately believes that the inventory is still intact, and could potentially be blindsided if it finds out about the disruptive impact at a time when the strategic inventory available is less than what it expects to be. The worst-case scenario is when the downstream supply chain finds out about the disruptive impact after the strategic inventory has fully run out.

Our model assumes that the downstream supply chain has established control processes in place that allow it to become aware of the situation as soon as a disruptive impact occurs.

3. t(D), the time at which the supply chain is disrupted:

When a disruptive event in the supply chain makes the downstream supply chain unable to meet customer demand, we say that a disruption in the supply chain has occurred. Therefore, the disruption is the effect, while the disruptive event is the cause.

The time of disruption may or may not be the same as the time of the disruptive event. There could be many different contributing factors for this, such as changing the BOM to accommodate the lost availability of a component, or satisfying customer demand through alternate products, etc. The predominant solution though is the deployment of inventory in the pipeline. The extent to which the time of disruption differs from the time of disruptive event depends on the amount of inventory in the pipeline.

For these reasons, the probability of disruption may or may not be the same as the probability of a disruptive event in the supply chain.

4. t(ASP), the time at which the alternate supply plan comes online:

At some point after the occurrence of a disruption in the supply chain, an alternate source of supply may come online. This alternate supply plan (ASP) could be either pre-selected or developed post-disruption or market-sourced, and it provides the components that were previously unavailable due to the disruption in the supply chain. Thus, the ASP enables the downstream supply chain to start meeting demand again.

a. Partial vs. Full alternate supply:

The alternate supply may provide the entire lost capacity or a portion of it. For our approach, we have assumed that the alternate supply provides 100% of the capacity that was previously lost due to the disruptive event. However, the methodology can be adjusted to account for partial alternate supply by increasing the lost contribution due to lost sales by a factor of $(1 - k)$, where k is the partial alternate supply factor.

b. Performance of the ASP:

Since the ASP is not the first choice for this component, it may have a lower performance than the first-choice base supply plan (BSP). This drop in performance could be on one or more dimensions such as cost, quality, reliability etc.

For our model, we focus on cost, but the analysis could be extended to include the impact on other dimensions as well.

For cost, the ASP is likely to increase the total cost of ownership for the OEM. The extent to which cost is likely to increase for a given component is a function of its supply factors such as concentration of suppliers, availability of spare capacity, sourcing from same supplier or from a new supplier, etc. The details of estimating the cost increase factor are discussed in formulas sub-section 3.4.3.

5. t(BSP), the time at which the base supply plan (BSP) comes online:

After the firm starts meeting customer demand through the ASP, due to the slight loss in performance of the supply chain under the ASP, the focus of the OEM now shifts towards moving supply from the alternate supply plan (ASP) back to the base supply plan (BSP).

The supply chain attains the BSP when the performance of the supply chain reverts back to pre-disruption levels on both output volumes and input costs. This is the earlier of either the disrupted node coming back to full functionality, or the ASP being fully integrated into the system (or some combination of the two), such that the total cost of material acquisition is brought back down to pre-disruption levels .

a. Extent to which pre-disruption level of performance is attained:

When the performance of the supply chain is back at pre-disruption levels, we say that the Base Supply Plan (BSP) has re-started. In practice, this may not occur for one or more of the different supply chain performance metrics mentioned earlier. For our model however, we assume that all metrics including input costs, attain the same level of performance as before disruption.

b. One supplier (either ASP or base) or combination of both ASP and base supplier:

The BSP may be attained with a single supplier (either the ASP or the original supplier) or two suppliers (both ASP and the original supplier). Our model assumes that the BSP is attained through a single supplier, which is the earlier of either the disrupted node coming back to full functionality, or the ASP being fully integrated into the system.

6. Downstream Inventory (DSI):

The amount of inventory that is present at the node and in the pipeline, expressed in days of sales. When expressed in time units, this is also the difference between the time of the disruptive event and the time of disruption.

DSI (days) = t(D) – t(DI)

a. Considering different kinds of inventory:

The supply network has inventory at multiple echelons, including supplier, transit, OEM, distributors, retailers, and even the customer. Since we are assessing the resiliency of the entire supply network, any inventory in the system that reduces the likelihood of a disruption in service to the end customer ought to be included in the assessment. Since the different echelons are in series, the DSI is additive. In other words,

DSI = Avg Inv (Supplier) + Avg Inv (Transit) + Avg Inv (OEM) + Avg Inv (Distributors) + Avg Inv (Retailers)

For our purposes, we consider all inventories at different supplier nodes that are downstream to the node at hand. However, the model can be adapted to include other inventory as well by replacing the supplier inventory with the sum of all inventories in the system as shown in the equation above.

b. Assessing Resiliency with Inventory vs. without Inventory:

When the inventory in the system is factored into our assessment model, the resiliency assessment is "with inventory". In other words, it estimates the resiliency of the system when the system has the historical average amount of inventory at each echelon.

However, a case can be made for not considering the presence of inventory in the system while assessing resiliency, because it could be argued that inventory is not a hard-coded feature of supply chain design in the same way as the choice of suppliers or the product BOM structures. The benefit of assessing resiliency without considering inventory is that it helps us focus on and improve the structural aspects of the supply network, and not let the presence of inventory mask structural risks. In such a case,

DSI = 0, and

t(D) = t(DI)

7. TTR, the Time To Recover for a node:

The TTR is the time elapsed from the occurrence of the disruptive impact that affected the productive capacity of the node, until the supply chain fully recovers from the disruption, which is when the base supply plan (BSP) comes back online.

TTR = t(BSP) – t(DI)

The TTR is a property that is characteristic of the node in the supply chain. For example, since a node is at the level of supplier-facility-process, the TTR is defined at the level of supplier-facility-process. However, the TTR can be defined for higher levels as well, such as facility, supplier, end-to-end supply chain etc., depending on the combination of nodes that are considered as disrupted.

8. TTF or Time to Failure:

The time to failure is the time it takes for the supply chain to fail to meet customer demand i.e., for supply chain disruption to occur. We assume that the available inventory, while it lasts, is used at 100% to meet customer demand.

$$\mathbf{TTF = t(D) - t(DI)}$$

Since t(DI) is offset from t(D) by the amount of inventory in the system, the TTF = DSI when expressed in days of inventory.

$$\mathbf{TTF = DSI\ (days)}$$

9. TTB or Time to Back-up:

It is the time taken by the sourcing team to bring the ASP fully on-line once the disruptive impact in the supply chain occurs.

$$\mathbf{TTB = t(ASP) - t(DI)}$$

If TTB < DSI, then the ASP comes on-line before the disruption in the supply chain occurs, thereby protecting the customer from shortages and thus preventing a supply chain disruption.

10. Black Out Period (BOP):

The BOP is the period of time during which the OEM is unable to meet customer demand. During the BOP, the supply of the component is disrupted due to unavailability of both capacity and inventory, as a result of which the customer is unable to receive the finished good.

$$\mathbf{BOP = t(ASP) - t(D)}$$

$$\Rightarrow \mathbf{BOP = [t(ASP) - t(DI)] - [t(D) - t(DI)]}$$

Therefore, $\mathbf{BOP = max\ (TTB - TTF, 0)}$

This is also the period of time elapsed between when the supply chain fails (Disruption) and when the back-up supply (ASP) comes online. During the BOP, the end product is not made, and results in a portion of demand volume becoming lost sales.

a. **Impacts of the Black Out Period:**

While there are many impacts of lost sales such as lost customer, lost market share, lost brand value, the most tangible and immediate impact of the BOP is in the form of lost contribution.

b. Partial vs. Complete Black Out:

The DSI in the system could be used to serve customers either at 100% demand rate over the time stocks last, or serve customers at less than 100% demand rate over a longer period of time. For our purposes, we do not make a distinction between the two scenarios, as in both cases, the total customer demand that is unmet is the same.

For the sake of simplicity, however, we assume complete black out, i.e., that the demand is met at 100% for DSI number of days after the Disruptive Impact occurs, and then there is a complete black out for (TTB – TTF) days.

11. Back Up Period (BUP):

The Backup Period is the period of time during which the customer demand is met through the alternate back-up source. During the BUP, the supplies of the component are sourced from an alternate source (ASP), and the system is not yet in steady state.

As mentioned in section 3.3.1 (4), the performance of the supply chain during the BUP may deteriorate in some dimensions, such as cost, quality, reliability, etc. However, due to the assumption made about the impact of the ASP on the supply chain performance, we consider the impact of the BUP only on increased input cost. Assessing the extent of cost increase is explained in detail in section 4.3.

The BUP is given by the time elapsed between when the alternate supplier comes online, and when then the supply chain system attains steady state again.

$$\mathbf{BUP = t(BSP) - t(ASP)}$$

$$\Rightarrow \mathbf{BUP = [t(BSP) - t(DI)] - [t(ASP) - t(DI)]}$$

$$\text{Therefore, } \mathbf{BUP = Max\ (TTR - TTB, 0)}$$

If there is only a single supplier in the market for a component, then the only path to steady state is if the node that is disrupted recovers back again. In this case,

$$\mathbf{TTR\ (Sole\ Source) = TTB}$$

$$\Rightarrow \mathbf{BUP\ (sole\ source) = 0}$$

3.3.2 Our Assumptions for ABC Company

In section 3.3.1, we saw that different definitions and assumptions were possible for each parameter. In this subsection, we list the assumptions made for each parameter, and briefly identify the impact of the assumption made on the modeling.

S.No.	Parameter	Assumption for ABC company
1	Time lag between Event and Disruptive Impact	t(DI) = t(E)
2	Probability of Disruptive Impact	p(DI) = p(E)
3	Knowledge of Disruption to OEM	Disruption known to OEM in real-time
4	Disruptive Impact at Node	Node is fully disrupted
5	Alternate Supply Plan (ASP)	Full alternate supply
6	ASP impact on supply chain performance	ASP impacts only cost
7	BSP performance	Pre-disruption levels are fully attained at BSP
8	Downstream Inventory (DSI)	Attribute pipeline inventory (link) to upstream node
		Inventory at OEM = 0
9	Black Out Period (BOP) characteristics	Complete blackout during BOP
10	Back Up Period (BUP) characterstics	Only cost impact during BUP

Figure 5 - Parameters, assumptions made, and impact of assumptions on model

The rest of the thesis adopts these assumptions. However, the model can be adjusted to reflect other assumptions as well.

In order to quantitatively assess the resiliency of the supply network system, we start with developing the model to assess the resiliency at a single node, which is at the supplier-process level, and then in the next section after that, we will look at how to roll it up and aggregate the quantitative assessment methodology to facilities, locations, and suppliers.

3.4 Quantitative Resiliency Assessment at a Single Node

The fundamental unit of measure in the BSR framework is the expected business impact due to the occurrence of a disruptive event at a node in the supply chain.

3.4.1 Expected Business Impact (BI)

The expected business impact (or BI) is the extent to which the bottom-line dollars of the firm are affected due to the occurrence of the disruptive event at a node, given the existing mitigation plans that are in place. Figure 6 shows expected business impact (BI) is obtained by multiplying the bottom-line financial impact of the loss of a node (disruption) with the probability of the occurrence of the disruption.

Expected BI ($) = Impact of Disruption ($) * Probability of Disruption

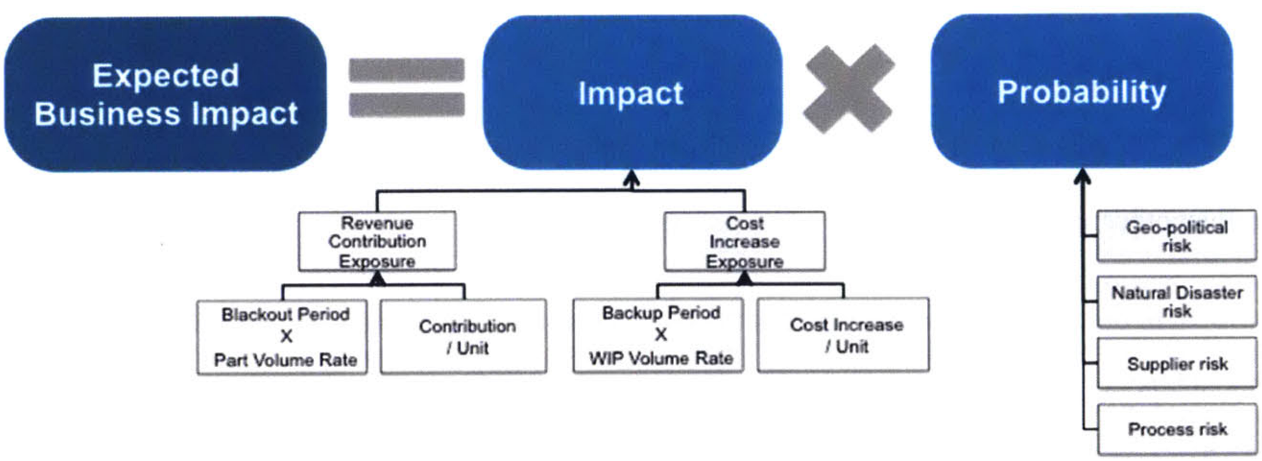

Figure 6 - Calculation of Expected Business Impact

Unlike some other resiliency assessment frameworks in the literature such as Risk Exposure Index (REI) (Simchi-Levi, 2014) that deal with top-line revenue dollars, we feel it may be preferable to deal with bottom-line contribution dollars. This is because our quantitative assessment includes a cost increase component as well, which is expressed in bottom-line dollars. Moreover, since the mitigation options are also evaluated based on their bottom-line cost dollars, this enables like to like comparisons of business impact reduction benefits with mitigation costs.

3.4.1.1 Impact of Disruption

The impact of a disruption in the supply chain occurs on both the supply and the demand sides. The total impact of a disruption on the supply chain is the sum of the impact on the demand side and the impact on the supply side.

Impact of Disruption ($) = Impact of Demand Disruption ($) + Impact of Supply Disruption ($)

On the demand side, the impact occurs in the form of lost contribution from lost sales, which we refer to as Contribution at Risk (CaR). On the supply side, the impact occurs in terms of the increased cost of supply, which we refer to as Cost to Recover (CtR).

Impact of Demand Disruption ($) = Contribution at Risk (CaR) ($)

Impact of Supply Disruption ($) = Cost to Recover (CtR) ($)

On both the demand and supply sides, the impact of the disruption is the product of total units exposed and the total impact per unit.

3.4.2 Contribution at Risk (CaR)

The contribution at risk (CaR) is the total contribution that is exposed during the Black Out Period (BOP), as a result of the occurrence of the disruption in the supply chain. The CaR is given by the contribution of a single unit of end product times the number of units of end product that are exposed during the BOP.

Contribution at Risk (CaR) ($) = Contribution at Risk per Unit (CaR) ($) / unit) * Units Exposed during BOP (units)

3.4.2.1 Units Exposed during BOP

The units exposed during the Black Out Period is the total number of units that are exposed to potential "lost sales" due to their unavailability for the end customer.

Units Exposed during BOP (units) = Rate of Sales (units / day) * BOP (days)

where BOP = t(ASP) – t(D) = Max(TTB – TTF, 0)

where TTB is Time to Backup = t(ASP) – t(DI),

and TTF is Time to Failure or Disruption = t(D) – t(DI) = DSI (in days)

- **Rate of Sales** is the sales that occur in a single day, for the Lines of Business (or finished goods models) under consideration. For a given disruption, the higher the Rate of Sales, the higher is the Expected BI.

Contribution at Risk per Unit (CaR / unit) = Contribution Loss per Unit ($ / unit) * Expected percentage of Lost Sales (%)

- **Contribution Loss per Unit** is the profit or contribution that is foregone when a unit remains unsold for any reason. It is not real dollars but an expected loss based on possible scenarios that could potentially occur in the future.

- **The Expected Percentage of Lost Sales** is the percentage of expected demand that results in lost sales due to unavailability of the finished good. Not all of the unmet end-customer demand results in lost sales, as some customers could potentially wait for the company's product or substitute with another product from the same company, which offsets some of the unmet customer demand.

  Not all types of products result in the same percentage of lost sales. Some of the factors that affect % lost sales are Brand Loyalty, uniqueness of the end product in the marketplace etc differ across products. The main factors that we believe are relevant to our supply chain are listed and explained below.

- **Brand Loyalty:** The more the customers are loyal to the brand of the company, the less likely they are to switch to a competitor product.

- **Degree of Internal Substitution Options:** The more options that customers have to choose from to substitute within the company's product portfolio, the less likely they will result in a lost sale for the company as a whole.

- **Switching Costs**: The less options that customers have to substitute with the competitors' product portfolios, the higher the switching cost for them, and therefore less likely that unmet customer demand would result in a lost sale. For commodities, switching costs are likely to be lesser.

3.4.3 Cost to Recover (CtR)

When a disruption occurs, it is likely that additional costs will be incurred in order to help the supply chain to recover and operate at steady state levels. The incremental cost incurred during this Backup Period (BUP) is defined as the Cost to Recover (CtR). The total CtR is the weighted average of the CtRs for the different recovery options, weighted by the expected likelihood of their deployment.

Recovery Options

While there may be other ASPs that are available to a company for each node in its supply chain, we will focus on the following two that we found to be the most commonly deployed in practice:

1. Using a different facility of the same supplier or
2. Shifting the source of supply to a different supplier.

However, the methodology can easily be adjusted to account for other recovery options by introducing them as more recovery options in the formula.

Volumes, Costs, and Expected Likelihood for each recovery option

Each of the above recovery options (i) has its corresponding units exposed (Vol_i), cost per unit incurred (C_i), and its expected likelihood of being deployed (f_i). Therefore, the overall expected cost to recover, CtR, is given by:

$$\textbf{Cost to Recover (CtR) (\$) = Sigma [} V_i \text{ (units) } * C_i \text{ (\$ / unit) } * f_i \textbf{]}$$

Units Exposed during BUP_i, V_i (units)

Even though the node has a TTR that is independent of the recovery option utilized, each recovery option (i) has a different $t(ASP_i)$, and therefore corresponds to a different BUP_i. During the BUP_i, the components are sourced at a higher cost per unit than the base supply plan (BSP). The number of units of the component that are affected during the BUP_i is given by:

$$V_i \textbf{ (units) = Rate of Sales (units / day) * [TTR (days) – } TTB_i \textbf{ (days)],}$$

$$\textbf{where TTR – } TTB_i = t(BSP) - t(ASP_i)$$

Cost increase per Unit during BUP_i (\$ / unit), C_i

The cost of deploying each recovery option i is likely to be different, with the "new supplier" option likely to cost more than the "same supplier, different facility" option.

For each recovery option, to obtain the total cost per unit, we add up all the additional costs incurred in order to operate during the BUP, i.e., from t(ASP) to t(BSP). This includes costs that are both bulk costs (fixed) and per-unit costs (variable).

Fixed costs are those costs that are incurred at the level of the entire recovery option (across all the units procured), such as the cost of identifying and bringing on-line a new supplier, or the cost of moving the tooling required for production to the new facility. Variable costs are those that are incurred at the level of each unit produced, such as the higher cost of production at the new facility or the increased cost of transportation.

We divide the fixed cost increase by the number of units procured during BUP_i to get the per-unit fixed cost, and add it to the variable cost to get the total increase in cost per unit.

$$\mathbf{C_i\ (\$ / unit) = variable\ cost\ (\$ / unit) + fixed\ cost\ (\$) / V_i\ (units)}$$

Expected likelihood of deploying Recovery Option, f_i

Also, the likelihood (f_i) of using one option over the other will be different across different nodes in the supply chain.

Estimating C_i, and f_i

The values of C_i and f_i may be driven by structural factors such as industry concentration in the supplier commodity, the options available with the current supplier(s), and the uniqueness of the component that is being manufactured.

Existing Supplier Capabilities

If the supplier has options available in the form of additional capacity, alternate production sites etc., then the probability of switching suppliers is reduced. This also leads to a smaller cost increase per unit.

Uniqueness of Component

The more standardized the component is, the more options the company has of finding alternate sources of supply. This reduces the cost and the probability of switching.

3.4.4 Probability of Disruption, (p)

The probability of disruption is the likelihood with which a disruption occurs in the supply chain. This is related to, but different from, the probability of a disruptive event, which is the likelihood with which a disruptive event occurs – since, as seen before, a disruptive event (one that disrupts the productive capacity of a node) may or may not lead to a disruption (when the end customer demand is not filled).

P (Disruption)

A disruptive event may or may not lead to a disruption in the supply chain depending on factors such as the presence of adequate inventory in the system.

P (Disruption) <= P (Disruptive Impact)

However, if downstream inventory (DSI) is zero, then

P (Disruption) = P (Disruptive Impact | DSI = 0)

P (Disruptive Impact)

The probability of a disruptive impact is the likelihood of occurrence of an impact at a node that leads to the disruption of its productive capability. Disruptive impacts may occur due to many factors such as natural disasters (e.g. the Thailand floods of 2011) or geopolitical instability or a manufacturing process failure. Broadly, these factors are classified as Internal and External factors as shown in Figure 7.

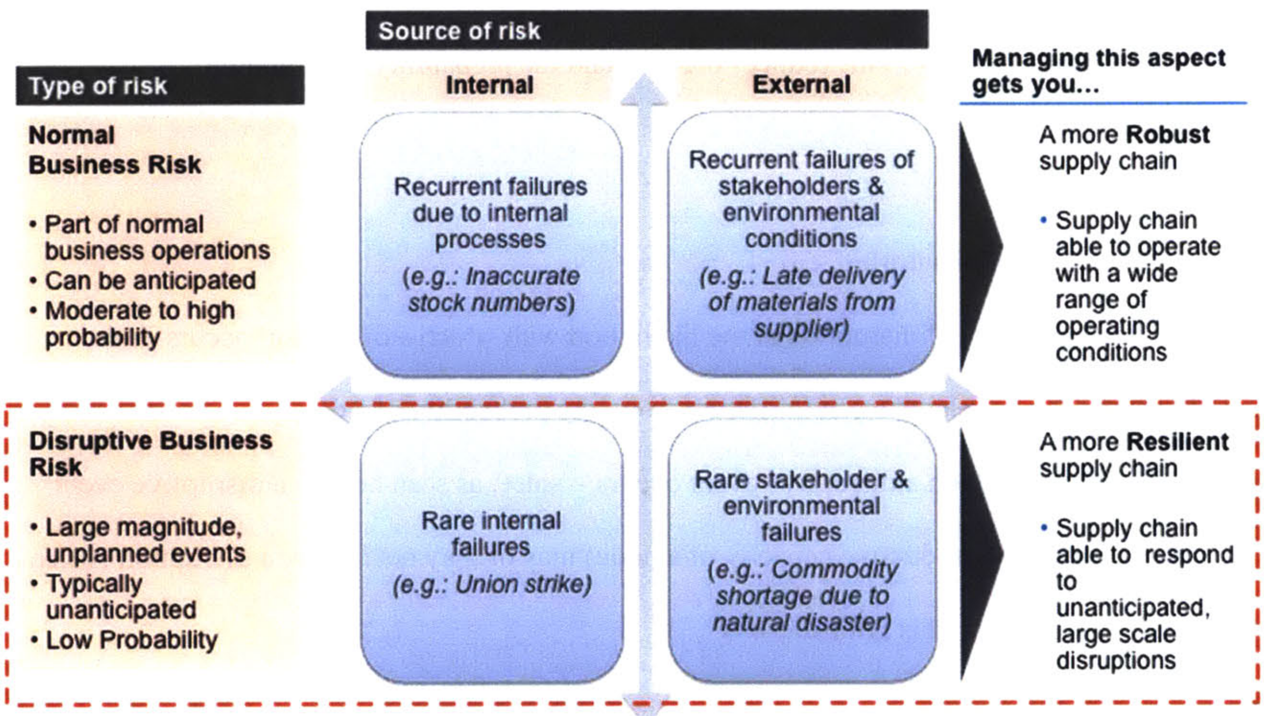

Figure 7 – Types and sources of risk

Internal Events

Internal events are those that affect a specific node or supplier, and hence are within his control. Some examples of internal events:

- Supplier Financial Stability (Altman's z score)

- Supplier Labor Issues
- Manufacturing Process Failures

External Events

External events are those that affect not only the given node or supplier, but also a larger set of nodes or suppliers. Therefore, they are outside the control of a given supplier. Some examples of external events:

- Natural Disasters
- Geopolitical Stability
- Government Regulations
- Raw Material Shortages

The preceding section outlines the development of the quantitative resiliency assessment at a node in the supply chain. The next section explains how the quantitative resiliency assessment is conducted at aggregated levels such as facility, supplier, location, and the commodity supply network.

3.5 Quantitative Resiliency Assessment at Aggregated Levels

The previous section outlined the quantitative assessment of resiliency at the node level. However, the quantitative assessment of resiliency can also be rolled up to aggregated levels of the supply chain such as the facility, the supplier, the location, and the end-to-end commodity supply chain level.

3.5.1 Output of Quantitative Resiliency Assessment at the Node

For each node, the quantitative resiliency assessment of the BSR reports the expected contribution at risk (CaR), the expected cost to recover (CtR), the probability of disruptive events (p), the time to recover (TTR) and the expected business impact (BI). As shown in Figure 8, this information is provided for minor disruptive events, major disruptive events, and all minor and major disruptive events taken together.

Supplier-Facility-Process	TTR (days)	p	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor disruptive events			a	b	a+b
MAJOR Disruptive Events			c	d	c+d
TOTAL			a+c	b+d	a+b +c+d

Figure 8 – Sample output of quantitative resiliency assessment at a node

The total expected business impact from minor disruptive events is the sum of the expected CaR for minor disruptive events and the expected CtR for minor disruptive events. This is likewise the same for major disruptive events as well.

Also, the total expected contribution at risk is the sum of the expected contribution at risk from minor disruptions and the expected contribution at risk from major disruptions. This is likewise true for expected cost to recover as well.

The total expected business impact is given by the sum of the expected business impact of minor disruptive events, as well as the expected business impact of major disruptive events. It is also given by the sum of the total expected contribution at risk and the total cost to recover.

3.5.2 Aggregating the Quantitative Resiliency Assessment at Aggregated Levels

When we aggregate the quantitative resiliency assessment to higher levels in the supply network such as the facility, supplier, location, or the entire commodity's supply chain, the expected CaR and the expected CtR are rolled up. The expected BI at the aggregated level is then computed by adding the aggregated expected CaR and the aggregated expected CtR.

Aggregating Expected CtR:

The expected CtR is additive when rolled up. This means that whether two or more nodes are in series or in parallel, the total expected CtR is given by the sum of the CtRs of each node. This is because, when a supply chain needs to fully recover from disruption by moving from the Alternate Supply Plan (ASP) to the Base Supply Plan (BSP), all of its nodes have to recover.

Aggregating Expected CaR:

The expected CaR is additive only when the nodes are in parallel. When the disrupted nodes are in series, the expected CaR is not additive, but a Max function.

When disrupted nodes are in Series

When a disruption affects two or more nodes that are in series, the total expected CaR is the maximum of the expected CaR of each of the nodes.

Exp CaR (nodes in series) = MAX [Exp. CaR (each node)]

This is because the impacts of the nodes that have lesser expected CaR are subsumed in the impact of the node with the largest expected CaR.

	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	24.3	15.0	39.3
MAJOR	13.2	2.7	15.8
TOTAL	37.5	17.7	55.2

+

	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	24.3	15.0	39.3
MAJOR	13.2	2.7	15.8
TOTAL	37.5	17.7	55.2

=

	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	24.3	30.1	54.4
MAJOR	13.2	5.3	18.5
TOTAL	37.5	35.4	72.9

Figure 9 – Sample of aggregating two nodes in series

When disrupted nodes are in Parallel

When a disruption affects two or more nodes that are in parallel, the aggregated expected CaR is the sum of the expected CaRs of each of the nodes.

Exp CaR (nodes in parallel) = SUM [Exp. CaR (each node)]

This is because the impact of the blackout of each of the nodes on the finished good is independent of the other, and therefore is cumulatively additive.

	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	24.3	15.0	39.3
MAJOR	13.2	2.7	15.8
TOTAL	37.5	17.7	55.2

+

	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	24.3	15.0	39.3
MAJOR	13.2	2.7	15.8
TOTAL	37.5	17.7	55.2

=

	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	48.6	30.1	78.7
MAJOR	26.3	5.3	31.7
TOTAL	75.0	35.4	110.3

Figure 10 – Sample of aggregating two nodes in parallel

By following the aggregation process outlined above, we can quantitatively assess the resiliency of the supply network not only at a node, but also at a facility, supplier, location, and the entire commodity supply chain. The next section introduces the qualitative assessment part of the BSR.

3.6 Qualitative Assessment

3.6.1 Scope of Quantitative Assessment:

A qualitative resiliency assessment intends to qualify the ability of a supply chain system to be resilient. A qualitative resiliency assessment attempts to assess a corporation's supply chain risk management capabilities.

3.6.2 The SCRLC Supply Chain Risk Management Maturity Mode Assessment

The Supply Chain Risk Leadership Council (SCRLC) has developed an assessment method referred to as the Supply Chain Risk Management Maturity Model that assesses a corporation's maturity in terms of supply chain risk management. This assessment sets a benchmark on how to rate a corporation's maturity in supply chain risk management and is adopted by many firms around the world. We want to use this method to assess the supply chain risk management processes of a company in combination with our BSR assessment to give a holistic quantitative and qualitative assessment of a company's resiliency.

3.6.2 Implementing the Assessment

The SCRLC Supply Chain Risk Management Maturity Model uses a total of 23 questions to assess a corporation's maturity in five major categories: Leadership, Planning, Implementation, Evaluation and Improvement. For each question, the users subjectively rank the maturity from 1 to, 5 with 1 being the least mature and 5 being the most mature. Table 1 shows a summary of the assessment. Table 2 shows the stages of maturity and definition.

Table 1: SCLRC assessment model categories and number of questions

Category	Number of Questions
Leadership	5
Planning	10
Implementation	3
Evaluation	3
Improvement	2

Table 2: SCLRC assessment model stages of maturity

Stages	Definition
1	Reactive
2	Aware
3	Proactive
4	Integrated
5	Resilient

3.6.3 Assessment Outputs

Once the assessment is complete, the model will generate the following sample outputs:

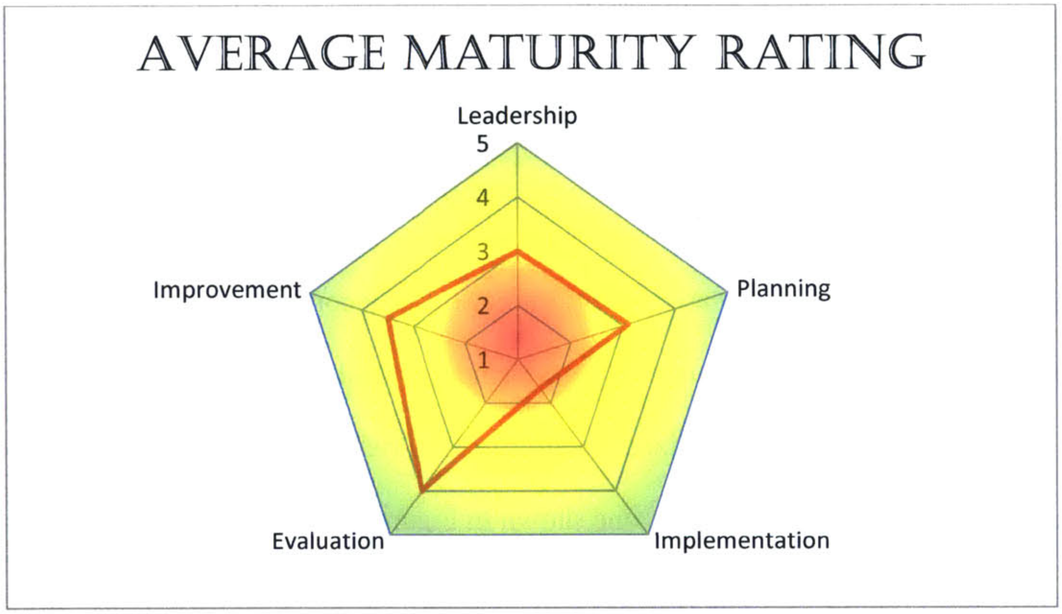

Figure 11: Pentagon showing results

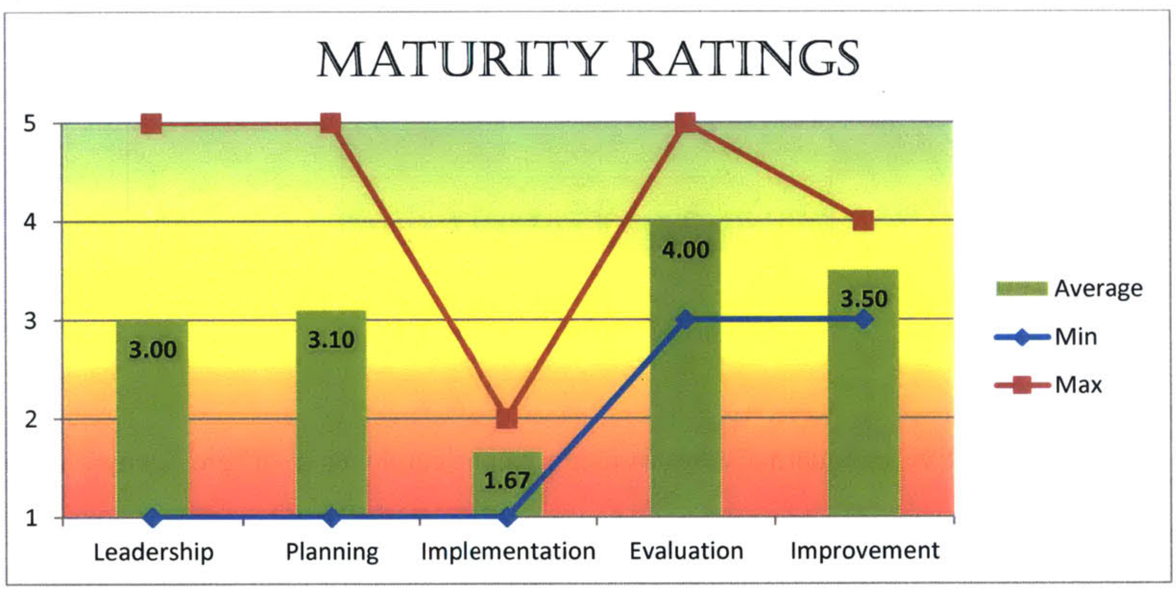

Figure 12: Bar chart and line chart of results

Figure 11 shows a pentagon output of the maturity of the five supply chain risk categories. Figure 12 shows a bar and line chart showing the min, max and average of the maturity ratings. From these outputs, the users can see where they stand in terms of their supply chain risk management maturity and identify areas for improvement.

3.7 Combining Quantitative and Qualitative Assessment into the BSR

BSR is a hybrid resiliency assessment framework that combines the quantitative assessment of resiliency with the qualitative assessment of resiliency to develop an overall risk score. This risk score is use to prioritized the allocation of risk mitigation dollars. Each node that is assessed will have a BSR such as the one shown in Figure 13.

	QUANT			QUAL
	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)	
minor	1281.2	92.5	1373.7	Medium
MAJOR	343.2	13.3	356.5	
TOTAL	1624.3	105.9	1730.2	

Figure 13 – Sample BSR input

The quantitative and qualitative assessments can be combined in different ways, and our thesis does not delve into that space. We only state that we believe it can be done.

3.8 Using Sourcemap as a visualization tool

Sourcemap is a supply chain tool that allows one to visualize a supply chain in a map view and supply network view. Sourcemap allows a user to see the flow of material from different suppliers and it overlays metrics on the supplier nodes. We used Sourcemap to visualize the expected business impact for each node of ABC Company's supply chain. This section outlined the methodology adopted to develop the BSR resiliency assessment framework. The next section talks about deployment of the BSR framework at ABC Company, followed by the results and discussion.

4. DEPLOYING BSR FRAMEWORK AT ABC COMPANY

4.1 Deploying the assessment framework for the ABC Supply Chain

The resiliency assessment framework outlined in the previous section was developed for deployment in the supply chain of ABC Company. The next step was to collect the required data and administer the resiliency assessment framework for it. A sub-section of the supply chain was identified and deployed in order to validate the approach and framework. Figure 14 shows the steps we tool to conduct the resiliency assessment.

Figure 14 - Development and deployment plan for ABC Company

For deployment, we focused on a single commodity, and on one supply chain within that commodity. The following section outlines the data requirements for the assessment framework developed in the previous section, the data that was collected and the data challenges therein.

4.2 Data Requirements

Qualitative Assessment Data

The full data plan includes data for the quantitative as well as the qualitative resiliency assessments. For the qualitative resiliency assessment, the data is collected through a survey administered to the senior executives in the sourcing organization.

Quantitative Assessment Data

Even though the resiliency assessment framework was developed with both the qualitative and the quantitative assessments, we were able to deploy only the quantitative assessment framework at ABC Company. Thus, the next section outlines the data requirements for the quantitative dimension of the BSR framework.

4.3 Data Collection and Data Challenges for Computing the expected BI

Section 4.2 outlines the data that are required to complete the resiliency assessment, with an emphasis on the quantitative dimension of the BSR framework. This sub-section explains why this data was needed, how the data request was made, the challenges in obtaining the data, and the surrogate data used, if any.

Figure 16 lists the different pieces of data required to compute the expected BI. The full list and their detailed definitions are given below:

1. **Processing stages:** *The different stages of manufacturing and processing of the material*

Different commodities have different processing stages such as Fabrication, Finishing, Painting, Assembly, Testing, etc. The number and type of these stages is important to know in order to map out the supply chain for the commodity. This information was obtained in interviews with commodity engineers and was relatively easy to obtain.

2. **Suppliers and Supplier facility locations:** *The list of suppliers for each processing stage, and their locations.*

To map out the supply chain, we need to know which vendor(s) are supplying which component(s) of the commodity, along its processing stages. This information was obtained in interviews with commodity engineers and was relatively easy to obtain.

3. **Rate of Sales Volume:** *For each end product, the volume of sales in FY14*

   Each commodity is used in a variety of end products, and in varying extents. For a given commodity, we identify the different end products that are affected, and the volumes that are impacted. For the purposes of risk assessment, we need only know which component is used in which end product, and a full BOM is not required.

   To compute the rate of sales volume, we take the past year's sales volumes by each model, and apply the percentage of those units that contain the commodity. The sales volumes are typically available with Corporate, while the extent to which different finished goods models contain different commodities are available with the supply chain organization. This data was relatively easy to obtain.

4. **Contribution Loss per Unit ($ / unit):** *For each end product, the contribution margins per unit*

The contribution margins vary across products, and the resiliency assessment is sensitive to the varying margins and the product mix. The contribution margin per unit for different models was available with finance or the strategy planning team, and was relatively harder to obtain due to the nature of its business sensitivity. If this information was not available, we make a simplifying assumption to consider all products as having the same contribution margin.

5. **Expected percentage of Lost Sales (%):** *For each end product, the extent to which the unavailability for product (for a reasonable time) would result in a lost sale*

Different end products will lose sales in different proportions of their stock-out demand. For example, products that enjoy higher loyalty from customers have lost sales % that is lower than that for those products that are commodities. Therefore, we need to identify the lost sales % for each end product model.

To estimate lost sales %, we could use contributing factors' data such as Brand Loyalty, extent to which OEM has internal product substitution options, extent to which competition has product substitution options etc. However, if this information is hard to obtain, we can approximate the methodology by taking a subjective factor as input from the sales and distribution organization. This process is described in the next sub-section on modifications to the methodology.

6. **(i)**: *Each Alternate Supply Plan (ASP) option such as producing in a different plant of the same supplier or producing with a different supplier*

This refers to different options available to the commodity team to bring the alternate supply plan (ASP) online, once a supply chain disruption occurs at a node. While there may be many options, the most common choices seem to be to source from the same supplier, different location, or to source from a different supplier altogether.

This information was not readily available in databases, and had to be taken as subjective input from the commodity managers based on their past experience and the present arrangements made. In our experience, this was readily provided to us. If this were not the case, we recommend using the above two options, with equal for either option, across all nodes.

7. **f_i:** *The likelihood of using each Alternate Supply Plan (ASP) option*

This is the estimated likelihood of using each of the above re-planning options after disruption. This information is fairly subjective and can be obtained from the commodity managers from a similar process as explained above. Since this information was not readily available, we used equal likelihood (0.5) for both options, across all nodes.

8. **C_i**: *The cost increase per unit for each option of re-planning production after disruption*

To estimate C_i precisely, we would need to know the average base cost of each component under the ASP and the additional fixed cost factors for each of the ASP options.

The price at which different vendors supply, combined with the volume mix, gives us the average price of the component for the ASP. This information was relatively easy to obtain.

The other fixed cost factors could be costs such as the cost of switching production, cost of switching suppliers, cost of management overhead etc. However, since this information was hard to obtain, we used just the increased variable cost of procurement as an approximation.

9. **P (Disruptive Impact):** *The probability of occurrence of a disruptive event in the supply chain*

To estimate the probability of occurrence of disruptive events, we use past history to evaluate the frequency of the different types of disruptive events.

Some of the major categories of disruptions are natural disasters, geo-political risk, supplier financial risk, manufacturing process failures etc. For each commodity, and each supplier location, the probabilities of such failures vary. We use past history as an indicator of future probabilities.

For external risk events such as natural disasters or geo-political risks, the data was available from expert third party agencies such as AIR, for a fee. For internal risk events such as manufacturing process failures, we rely on the past experience of the commodity managers.

10. **TTR:** *For each node, the time elapsed between when a disruptive impact occurs and when that node is back to full functionality*

    This information was obtained from commodity managers and suppliers based on their mutual assessment of the capabilities of the supplier facility. This information was relatively harder to precisely obtain compared to some of the other data mentioned in this section, and can also be subjective.

11. **DSI:** *For each node, how much inventory is available at the node and downstream*

    The amount of inventory kept at each node in the supply chain, converted into number of days of sales it represents. This information was usually available with the commodity engineers, and was easily available.

As this section shows, some data were easier to obtain than others. For those data that were not directly available, surrogates were created, and the methodology was modified slightly to accommodate these approximations, and the assessment was carried out.

5. RESULTS

The purpose of the thesis is to develop a hybrid resiliency assessment framework and deploy it on a supply chain and gather insights from the outputs. Therefore, we applied the BSR framework to assess the resiliency of ABC's supply chain for one commodity. Due to limited project scope, we only completed a detailed quantitative assessment to find the expected business impact dollars. The qualitative assessment will be part of a later study. To conduct our quantitative assessment, we collected data for one commodity of ABC Company through its commodity managers. We then applied our BSR framework to calculate the expected business impact (BI) for each node in ABC's supply chain. Finally, we inserted the data into Sourcemap to visualize the BIs on a map, where we analyzed the data.

5.1 ABC's Supply Chain

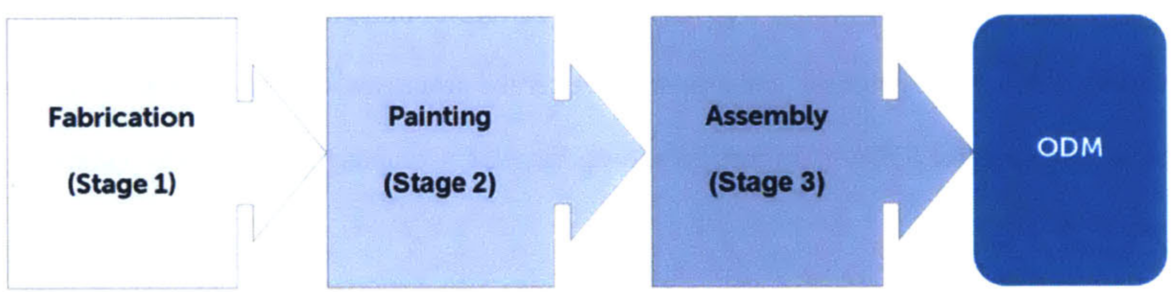

Figure 15 - Flow of ABC's supply chain for a commodity

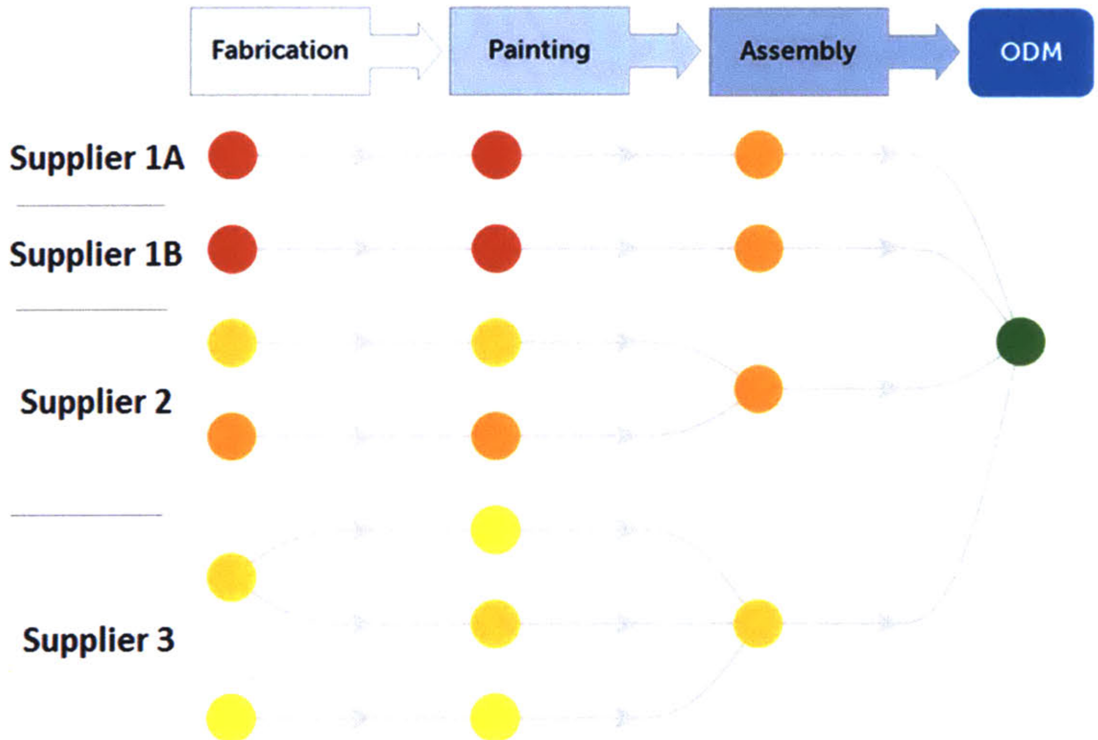

Figure 16 - Network view of ABC's supply chain for a commodity

ABC Company sourced their commodity from vendors throughout China and Taiwan. Figure 15 shows that each vendor was responsible for one or more of the following three processes: fabrication, painting, and assembly. After the processes, they all flow to the Original Design Manufacturer (ODM). Figure 16 shows that ABC Company has 3 main suppliers.

5.2 Calculating Business Impact of Supply Chain Nodes

We received data for 134 parts from the commodity managers. We then segmented the data to show how they flowed through the 3 stages of ABC's supply chain. From the data, we calculated the Contribution at Risk (CaR) and Cost to Recover (CtR) and ultimately the expected Business Impact (BI) flowing through each node in the supply chain. We then formatted the data into a Sourcemap-friendly format and inputted the data into Sourcemap for visualization.

	TTR (days)	prob (%)	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	20	80%	1281.16	92.53	1373.69
MAJOR	60	5%	343.17	13.35	356.51
TOTAL			1624.33	105.87	1730.20

Figure 17 - Sample expected Business Impact calculation for a node

Figure 17 shows a sample expected business impact calculation for a node. We separated the disruption events into minor and major events. Minor events have a shorter time to recover (TTR), but higher probability of occurrence. Major events have a longer time to recover (TTR), but lower probability of occurrence. We then calculate the Contribution at Risk (CaR) and Cost to Recover (CtR) for the minor and major events then sum them up to get the total expected Business Impact.

5.3 Expected Business Impact outputs

In this section, we have compiled several different views of our data. Each view provides different insight regarding the results.

5.3.1 Business Impact outputs chart form

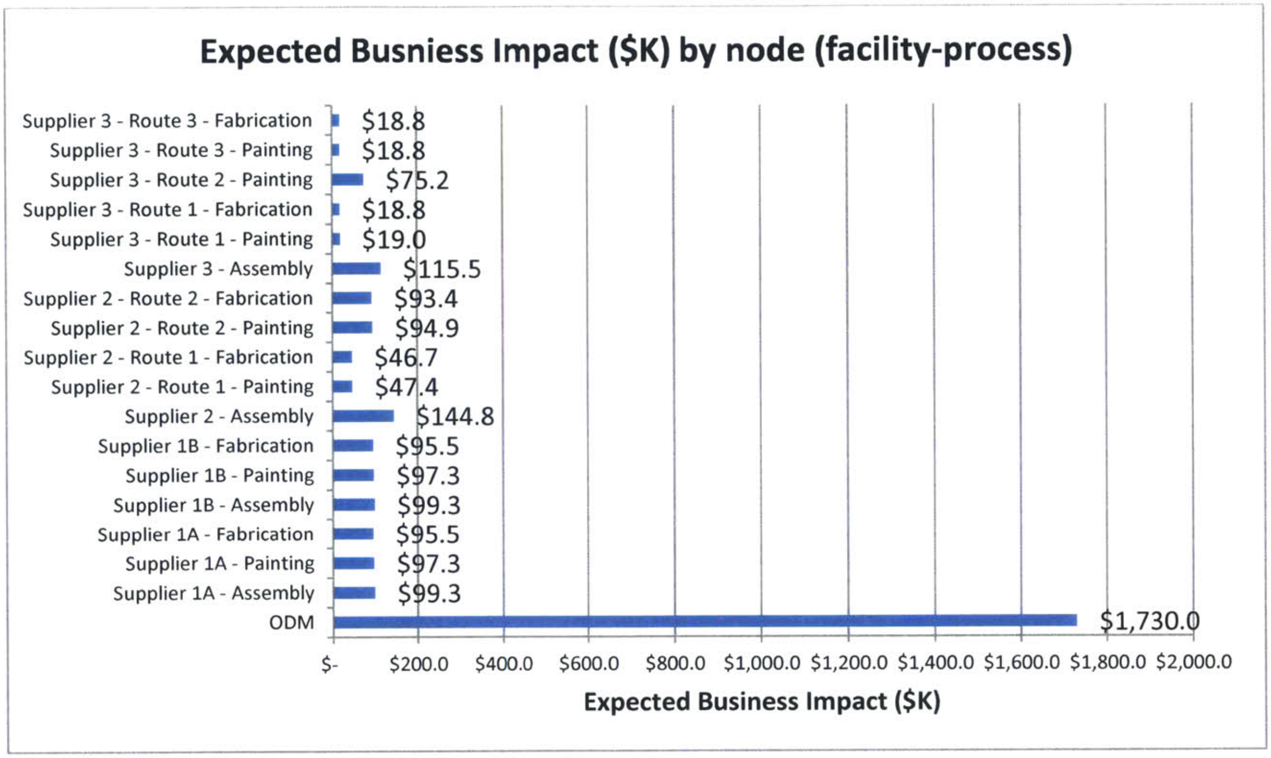

Figure 18 – Bar chart showing Expected Business Impact scores sorted by node (facility-process)

Figure 18 shows expected business impact dollars sorted by facility-process node. ODM clearly has the highest expected business impact of $1730K. The second highest expected business impact is at supplier 2 of $144.8K at its assembly process. The third highest expected business impact is at supplier 3 of $115.5K at its assembly process.

5.3.2 Expected Business Impact outputs from Sourcemap

Figure 19 - Expected Business Impact scores output from Sourcemap – Map view

Figure 19 shows the expected Business Impact information in a map view from Sourcemap. Not only are the expected business impacts dollar amounts shown, but the flow of materials from each location to another are also shown. Location A, where the ODM resides, has the highest expected business impact of $1,730K. Location B is near location A but does not get included in the expected business impact calculation for location A. Sourcemap has a zoom in functionality to see more details up close.

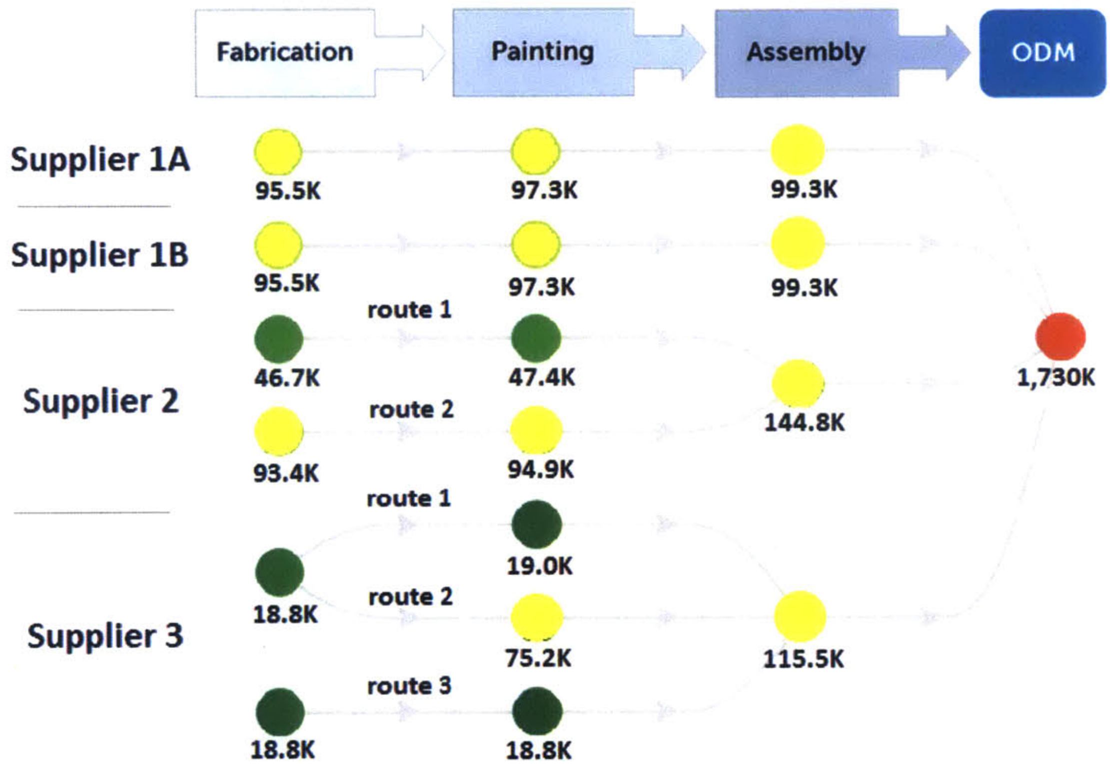

Figure 20 - Expected Business Impact scores output from Sourcemap – Supply Chain Network view

Figure 20 shows the expected Business Impact dollars in supply chain network view. This view sheds some new light on the associated expected business impact in the various stages of the supply chain. Figure 20 shows that the ODM has the expected highest business impact at $1,730K. The assembly stage for supplier 2 has the second highest expected business impact at $144.8K. All suppliers have the highest expected business impacts during the assembly stage and this is because the cumulative downstream inventory (DSI) is lower here than the upstream painting and fabrication stages.

5.3.3 BSR format view of Expected Business Impact for supply chain

F - Supplier 1A	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	0.0	14.4	14.4
TOTAL	0.0	95.5	95.5

FP - Supplier 1A	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	1.8	14.4	16.1
TOTAL	1.8	95.5	97.3

FPA - Supplier 1A	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	3.8	14.4	18.2
TOTAL	3.8	95.5	99.3

F - Supplier 1B	CaR ($K)	CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	0.0	14.4	14.4
TOTAL	0.0	95.5	95.5

FP - Supplier 1B	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	1.8	14.4	16.1
TOTAL	1.8	95.5	97.3

FPA - Supplier 1B	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	3.8	14.4	18.2
TOTAL	3.8	95.5	99.3

F - Supplier 2 - Route 1	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	39.7	39.7
MAJOR	0.0	7.0	7.0
TOTAL	0.0	46.7	46.7

FP - Supplier 2 - Route 1	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	39.7	39.7
MAJOR	0.7	7.0	7.8
TOTAL	0.7	46.7	47.4

FPA - Supplier 2	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	119.0	119.0
MAJOR	4.7	21.1	25.8
TOTAL	4.7	140.1	144.8

F - Supplier 2 - Route 2	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	79.4	79.4
MAJOR	0.0	14.0	14.0
TOTAL	0.0	93.4	93.4

FP - Supplier 2 - Route 2	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	79.4	79.4
MAJOR	1.5	14.0	15.5
TOTAL	1.5	93.4	94.9

ODM	TTR (days)	p	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	20	80%	1281.2	92.5	1373.7
MAJOR	60	5%	343.2	13.3	356.5
TOTAL			1624.3	105.9	1730.2

F - Supplier 3 - Route 1	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	16.0	16.0
MAJOR	0.0	2.8	2.8
TOTAL	0.0	18.8	18.8

FP - Supplier 3 - Route 2	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	16.0	16.0
MAJOR	0.2	2.8	3.0
TOTAL	0.2	18.8	19.0

F - Supplier 3 - Route 2	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	16.0	16.0
MAJOR	0.0	2.8	2.8
TOTAL	0.0	18.8	18.8

FP - Supplier 3 - Route 2	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	63.9	63.9
MAJOR	0.0	11.3	11.3
TOTAL	0.0	75.2	75.2

FPA - Supplier 3	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	95.8	95.8
MAJOR	2.7	17.0	19.6
TOTAL	2.7	112.8	115.5

F - Supplier 3 - Route 3	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	16.0	16.0
MAJOR	0.0	2.8	2.8
TOTAL	0.0	18.8	18.8

FP - Supplier 3 - Route 3	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	16.0	16.0
MAJOR	0.0	2.8	2.8
TOTAL	0.0	18.8	18.8

Figure 21 – Exploded BSR view of commodity Supply Chain Network

Figure 21 shows the expected business impact calculation view of the supply chain network. Figure 21 is an exploded view of the calculations that arrives at the final expected business impact numbers for figure 20. Due to the higher likelihood of the minor disruptions happening, the expected business impacts are higher for all cases for minor disruption events.

5.4 Aggregated Business Impact outputs from supply chain levels

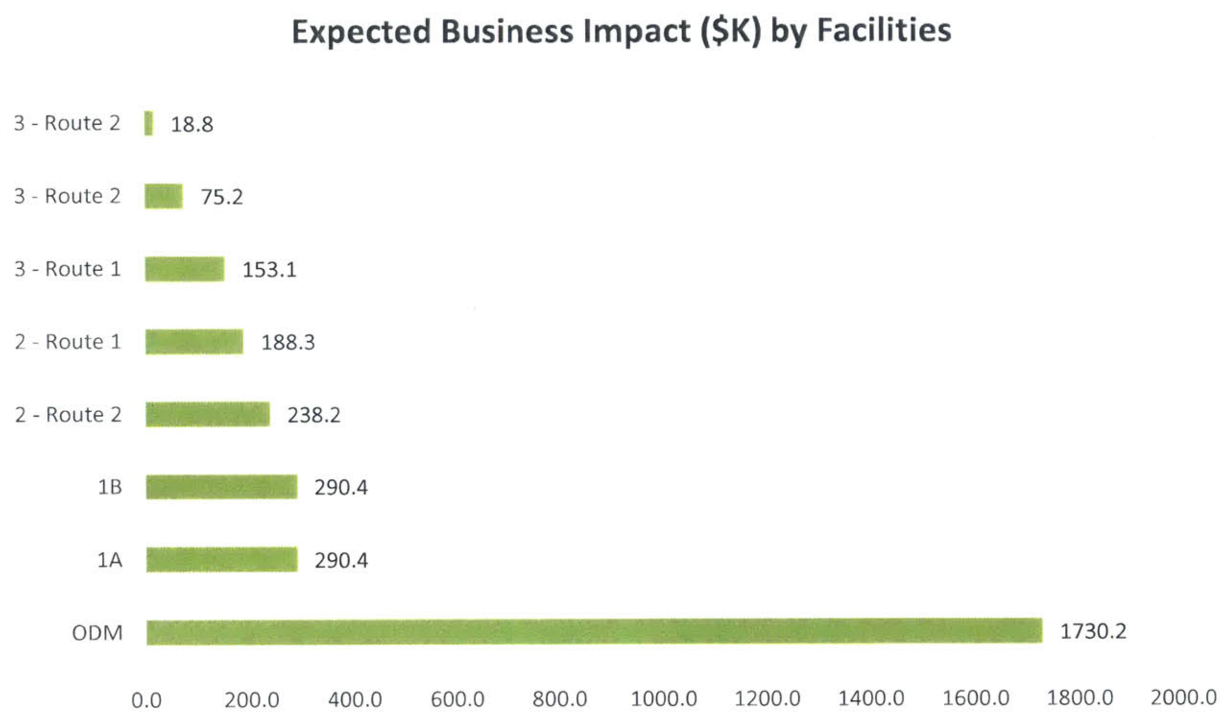

Figure 22 – Expected Business Impact aggregated by supplier facilities

Figure 22 shows the expected business impact dollars sorted by facilities. ODM facility has the highest expected business impact of $1,730K. ODM's expected business impact is highest because we did not consider ODM inventory in our calculation. We do not consider ODM inventory because as per ABC Company, the inventory at the ODM is kept for customer service purposes, and not for increasing supply chain resiliency. Facilities 1A and 1B have the second highest expected business impact of $290.4K.

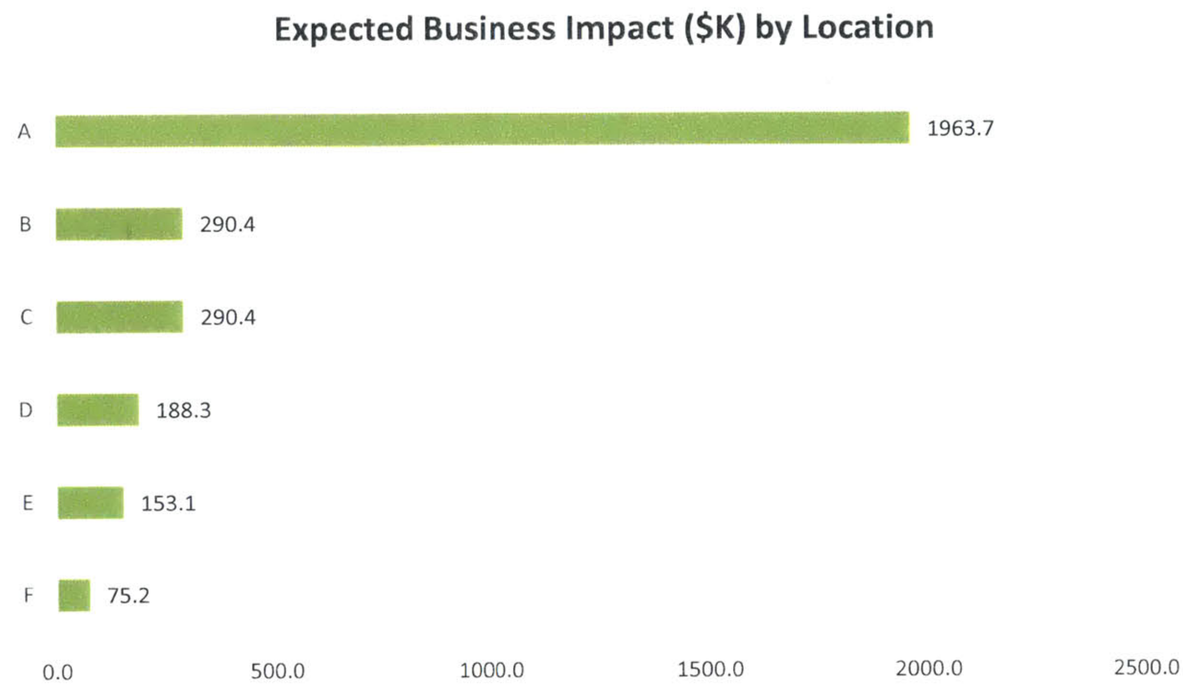

Figure 23 – Expected Business Impact aggregated by supplier locations

Figure 23 shows the expected business impact dollars sorted by locations. Location A has the highest expected business impact of $1,963.7K. Figure 19 shows where location A is. Location A has the highest expected impact because of the proximity of two facilities located in that area. Locations B and C have the second highest expected business impact of $290.4K.

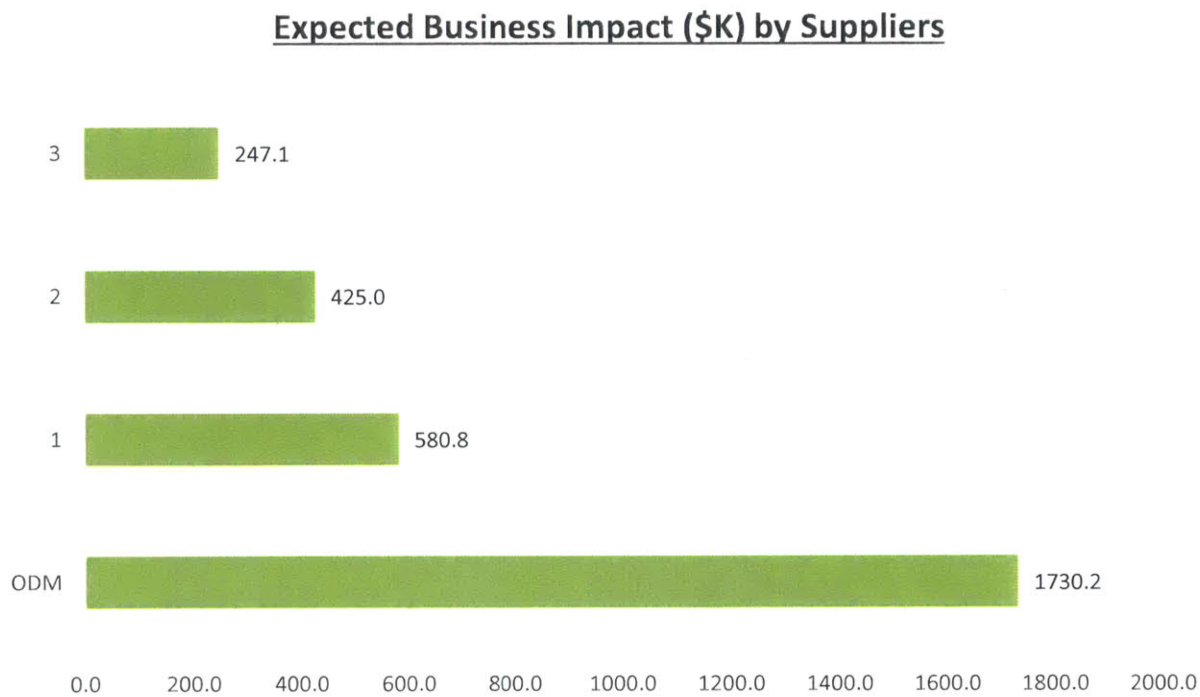

Figure 24 – Expected Business Impact aggregated by suppliers

Figure 24 shows the expected business impact dollars sorted by suppliers. ODM has the highest expected business impact of $1,730K. Supplier 1 has an expected business impact of $580.8K. Supplier 2 has an expected business impact of $425K. Supplier 3 has an expected business impact of $247.1.

5.5 Total commodity expected business impacts and insights

The overall expected business impact of the one commodity in entirety is $2,968K. ABC Company would need to put mitigation plans and resources in order to lower the total business impact dollar amount.

5.6 Generating Response Curves using Simulation

Computing the expected business impact at the aggregated levels of facilities, suppliers, locations, and the entire commodity allows us to focus on those facilities, suppliers, or locations that contribute the most to the commodity's risk. For these critical entities, we simulated the response of the commodity supply chain's expected BI by varying the values of different input factors such as TTB, TTR, DSI, p(Major Events), p(Minor Events) etc. When we keep all other parameters constant (ceteris paribus), the response curves gave us the sensitivity of the commodity expected BI for the input parameter that is being varied.

5.6.1 Response curve for Inventory at ODM

When the ODM inventory is increased from zero to 15 days, we see that the total expected business impact for the commodity decreased from nearly $3M to $1.5M. However, while there is a rapid decrease in the commodity's expected BI from 0 to 7 days of inventory, the decrease in commodity's expected BI for every additional day of inventory after 7 days decreases.

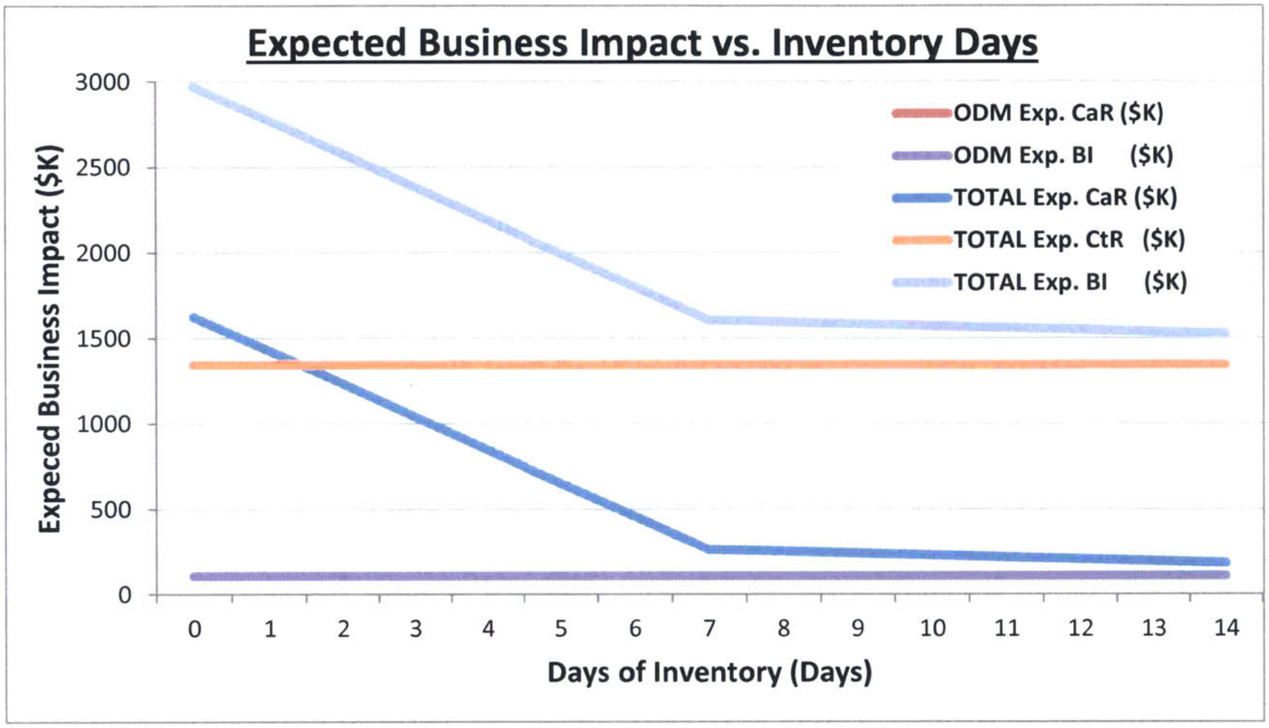

Figure 25 - Response Curve for ODM Inventory vs. expected BI.

In figure 25, we see that the amount of days of inventory impacts the Contribution at Risk (CaR) for ODM. For every additional day of inventory up to seven days, there is nearly a $200K marginal decrease in total expected BI for the commodity supply chain at the ODM. Whereas after 7 days of inventory, the marginal benefit from holding an additional day of inventory is around $10K only.

5.6.2 Response curve for P(Disruptive Impacts) at ODM

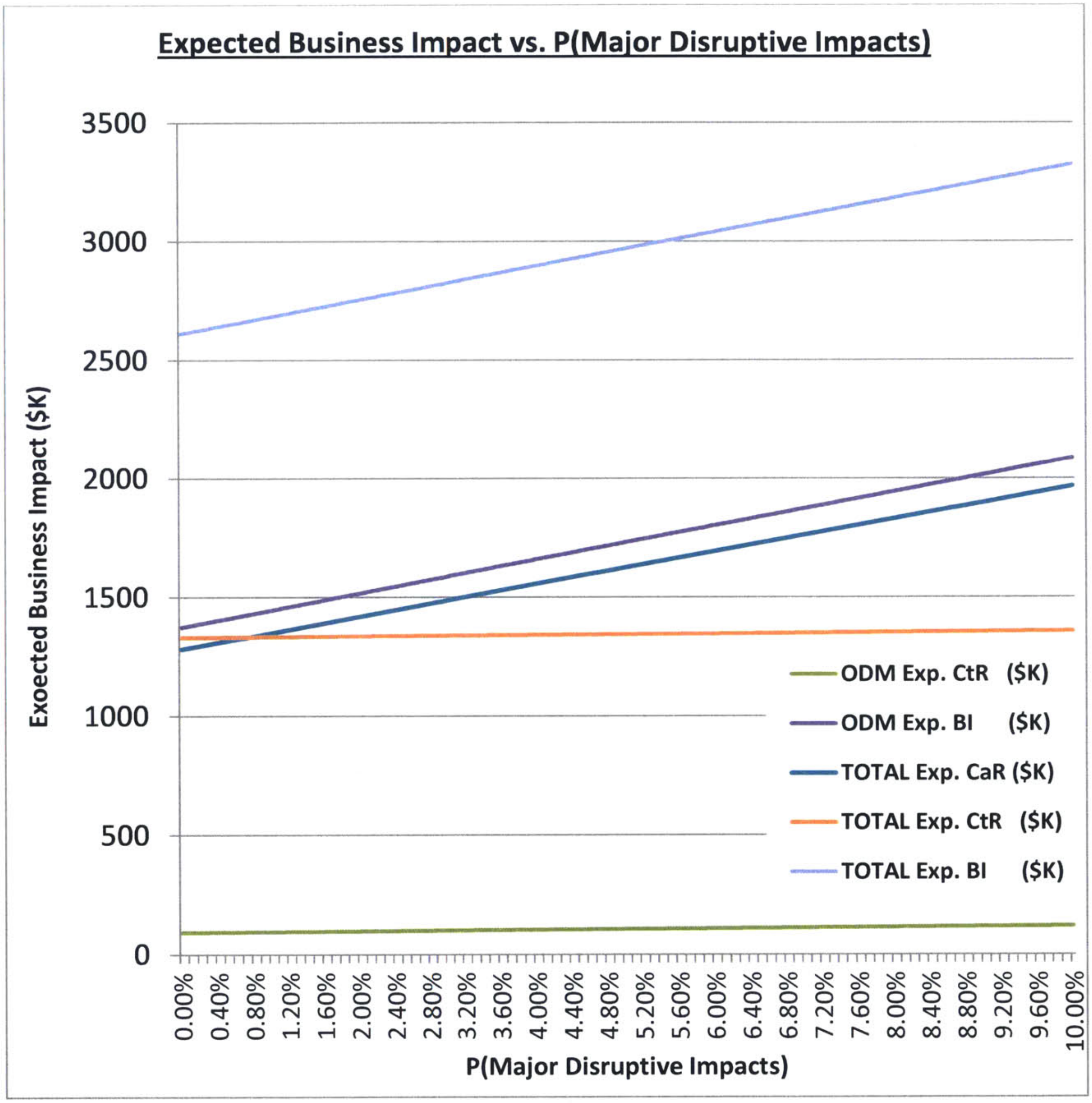

Figure 26 - Response Curve for ODM P(Major Disruptive Impacts) vs. expected BI

In figure 26, we see that when the P(Major Disruptive Impacts) at the ODM increases from 0% to 10% in small increments, we see that the expected BI of the commodity supply chain increases from $2.6M to $3.3M.

Similarly, figure 27 shows the response of commodity expected BI to varying the P(Minor Disruptive Impacts) from 0% to 10% from 1.6M to 1.8M.

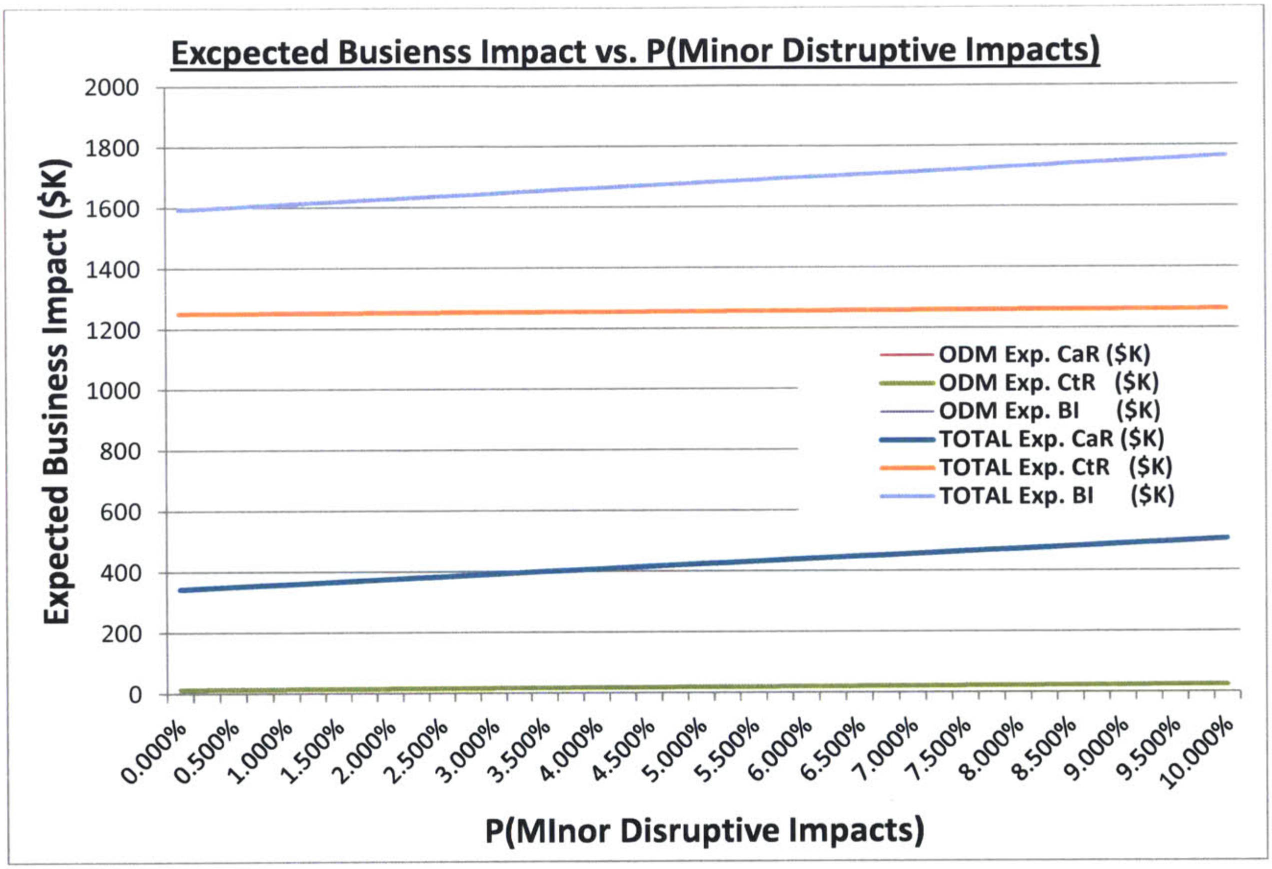

Figure 27 - Response Curve for ODM P(Minor Disruptive Impacts) vs. expected BI

At ABC Company, the values for P (Major Disruptive Impacts) and P (Minor Disruptive Impacts) at the ODM are 5% and 80%, which correspond to expected BI of the commodity of around $3M.

Therefore, we see that the response of the commodity expected BI varies for different parameters and with each node. Such response curves can be generated for each parameter and at each node or set of nodes. This will help us identify the most sensitive input parameters for this commodity, so that we can focus on those for immediate mitigation efforts.

Now that we have shown the expected business impacts for ABC Company's supply chain for one commodity, in the discussion section we will provide the insights we have gathered and the recommendations we propose to improve ABC Company's supply chain.

6. DISCUSSION OF RESULTS

6.1 Interpretation of Findings and Results

This section discusses the interpretation of our findings and results for the company. We start with analyzing the Balanced Scorecard of Resiliency (BSR) output for a single node, followed by interpreting what the results mean at higher levels of aggregation such as facilities, suppliers, locations, and entire commodity, supply chains. Because the deployment phase of our study covered only the quantitative assessment of resiliency, we will restrict our discussion to the quantitative output of the BSR, which is the expected Business Impact (BI).

6.2 Interpreting the expected BI for a Node

The quantitative dimension of the BSR provides an output as shown in figure 28:

Supplier-Facility-Process	TTR (days)	p	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor disruptive events	60	80%	24.3	15.0	39.3
MAJOR Disruptive Events	180	5%	13.2	2.7	15.8
TOTAL			37.5	17.7	55.2

Figure 28 – Sample BSR output

6.2.1 Comparing minor vs. major disruptive events' expected BIs:

The first column lists the type of disruptive events for which the rest of the scorecard provides assessments, and the universe of disruptive events has been divided into minor and major disruptions.

For minor disruptive events at this node, it has a 0.8 chance of having one occurrence within the next period of evaluation (usually 1 year), and takes 60 days for the node to fully recover or for the ASP to become the BSP i.e., the TTR = 60 days. Similarly, the major event has a probability of 0.05 chance of occurring, with a TTR of 180 days.

Given this data, and the overall structure of the supply chain for this commodity, we find that minor disruptive events have a total expected BI of $39.3K, whereas major disruptive events have a total expected BI of $15.8K. This may potentially be counter-intuitive, given that one might expect the major disruptive events to have a greater business impact. However, major disruptive events tend to have a slightly smaller expected BI due to their relatively less common occurrence i.e., lower probability of occurrence.

6.2.2 Comparing expected CaR vs. expected CtR:

The expected CaR is higher than the expected CtR for both major and minor disruptive events at this node. This is true even though the blackout period (BOP) is shorter than the backup period (BUP) because lost contribution/day is typically higher than increased cost of operation per day.

6.2.3 Node-level Insights

Figure 29 below shows the expected BI for each node of the commodity's supply chain. As can be seen, there are 15 nodes, which include 4 different facilities, 3 suppliers, and 4 manufacturing processes.

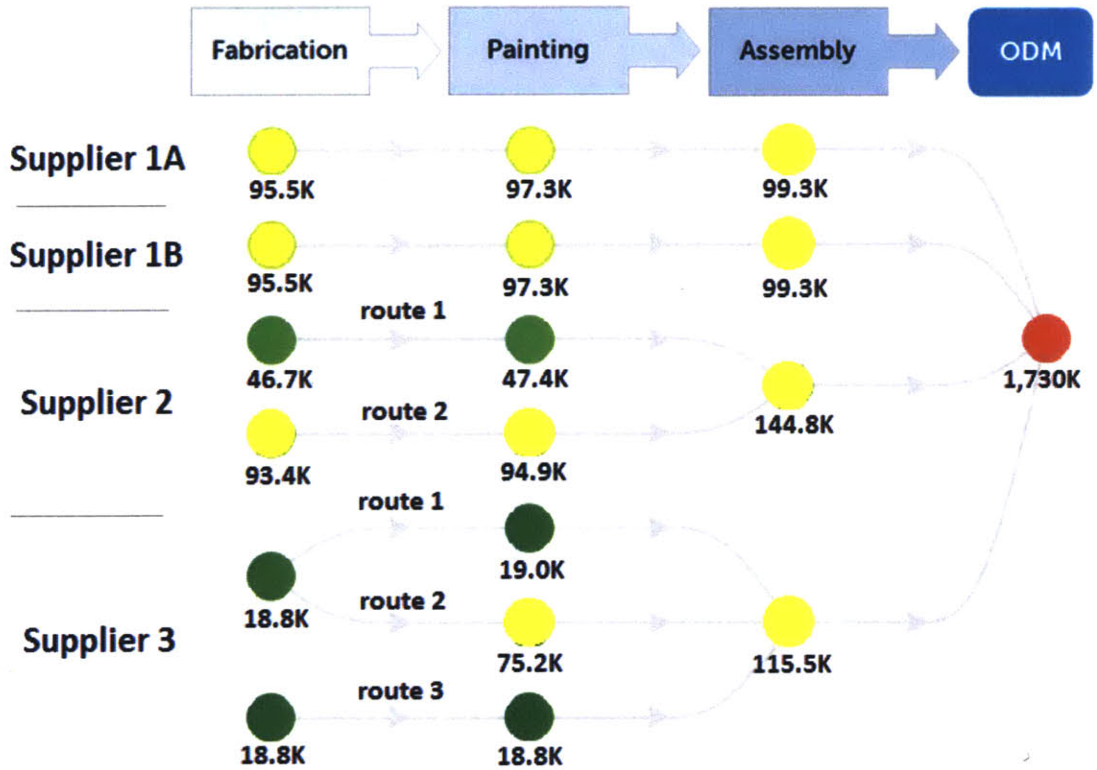

Figure 29 – Network View of ABC Company

The expected BI for Supplier locations 1A and 1B are typically higher than that for Supplier 3. This is because the volume of materials flowing through Supplier locations 1A and 1B are higher than the volume flowing through supplier 3. The same reason explains why the expected BI for the ODM is much higher than the expected BI of any of the nodes, even though the TTR of the ODM is relatively shorter.

The expected BI is higher for supplier locations 1A and 1B for the assembly process compared to the same supplier-facility's fabrication and painting processes. This is due to the relatively low levels of downstream inventory (DSI) at assembly compared to fabrication and painting. Therefore the supplier-location-process 1A-assembly has an expected business impact of $99.3K over the next one year.

The expected BI is lower for the painting processes of supplier 3 at its route 1, route 2, and route 3 paths compared with the painting process of supplier locations 1A or 1B. This is because in the case of supplier locations 1A or 1B, they are single-source for their downstream assembly stage, whereas in supplier 3's route 1 and route 2, the painting process is multi-sourced.

6.3 Interpreting the expected BI at Aggregated Levels

Section 6.2 shows how the expected BI was interpreted to provide us a picture of the resiliency at a node and comparisons across nodes. In this section, we will use interpret the expected BI at aggregated levels to understand the resiliency at facilities, suppliers, locations, and the entire commodity supply chain.

6.3.1 Assessing Supplier Facilities

The resiliency of a supplier facility is measured by the expected business impact of losing that supplier. When a supplier facility is disrupted, we have all the nodes that represent the different processes of a single supplier facility being disrupted simultaneously. Such an outcome is possible, for example, when the disruptive event is a labor issue at the facility.

For supplier facility 1A, we have the following computations:

1A Fabrication	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	0.0	14.4	14.4
TOTAL	0.0	95.5	95.5

1A Painting	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	1.8	14.4	16.1
TOTAL	1.8	95.5	97.3

1A Assembly	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	3.8	14.4	18.2
TOTAL	3.8	95.5	99.3

=

FACILITY 1A Total	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.00	243.53	243.53
MAJOR	3.80	43.08	46.88
	3.80	286.61	290.41

Figure 30 – Expected Business Impact calculations for supplier facility 1A

Exp. CaR (1A) = MAX [Exp CaR (1A Fabrication, 1A Painting, 1A Assembly)]

= MAX [0, 1.8, 3.8] = 3.8K USD

Exp. CtR (1A) = SUM [Exp CtR (1A Fabrication, 1A Painting, 1A Assembly)]

= SUM [95.54, 95.54, 95.54] = 286.6K USD

Exp. BI (1A) = Exp. CaR (1A) + Exp. CtR (1A)

= 3.8K + 286.6K = 290.4K USD (due to rounding)

When we compute this for all facilities in the commodity supply chain, we arrive at figure 31.

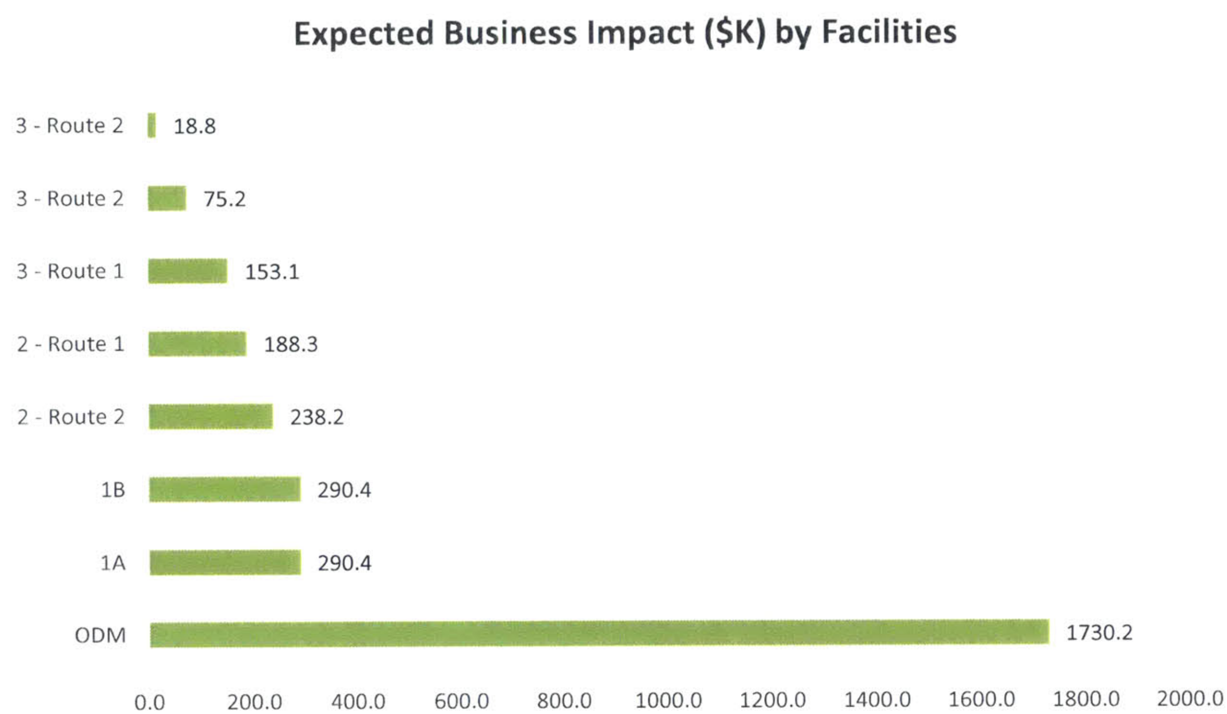

Figure 31 – Expected Business Impact aggregated by facilities

Figure 31 shows different supplier facilities have different expected BIs. Among the non-ODM facilities, supplier facilities 1A and 1B have the highest expected BIs. This is because they have all 3 processes – Fabrication, Painting, and Assembly – at the same facility. This increases the expected BI in two ways: aggregating more components at one facility, and also having reduced inventory between processes. The latter signifies a pattern we observed repeatedly, where "lean" or "just in time" operations that had lower inventory exposed the supply chain to greater risk. One way to reducing this risk would be to require the supplier to hold more strategic inventory in the pipeline (SIP). However, the perils of inventory in the supply chain have been well documented in literature, and all options should be considered as alternatives for reducing the risk.

One way in which the expected BI can be reduced is to decrease the Backup Period or the BUP. In this case, that would mean having an alternate supply plan (ASP) more online by potentially paying for contingent contracts. A deeper analysis of mitigation options will be covered in section 6.3.2.

6.3.2 Assessing Suppliers

The resiliency of a supplier is measured by the expected business impact of losing that supplier. When a supplier is disrupted, we have all the nodes that represent the different processes and facilities of a supplier being disrupted simultaneously. Such an outcome is possible, for example, when the disruptive event is a supplier bankruptcy.

For supplier 1, we have the following computations:

1A Fabrication	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	0.0	14.4	14.4
TOTAL	0.0	95.5	95.5

1A Painting	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	1.8	14.4	16.1
TOTAL	1.8	95.5	97.3

1A Assembly	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	3.8	14.4	18.2
TOTAL	3.8	95.5	99.3

+

1B Fabrication	CaR ($K)	CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	0.0	14.4	14.4
TOTAL	0.0	95.5	95.5

1B Painting	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	1.8	14.4	16.1
TOTAL	1.8	95.5	97.3

1B Assembly	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.0	81.2	81.2
MAJOR	3.8	14.4	18.2
TOTAL	3.8	95.5	99.3

=

SUPPLIER 1 - Total	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.00	487.06	487.06
MAJOR	7.60	86.15	93.75
	7.60	573.22	580.82

Figure 32 – Expected Business Impact calculations for suppliers 1A and 1B

Exp. CaR (1) = SUM [Exp CaR (1A, 1B)]

= 3.8K + 3.8K = 7.6K USD

Exp. CtR (1) = SUM [Exp CtR (1A, 1B)]

= 95.5K + 95.5K + 99.93 + 95.5K + 95.5K + 99.93 = 573.2K USD

Exp. BI (1) = Exp. CaR (1) + Exp. CtR (1)

= 7.6K + 573.2K = 580.8K USD (due to rounding)

When we compute this for all suppliers in the commodity supply chain, we arrive at figure 33:

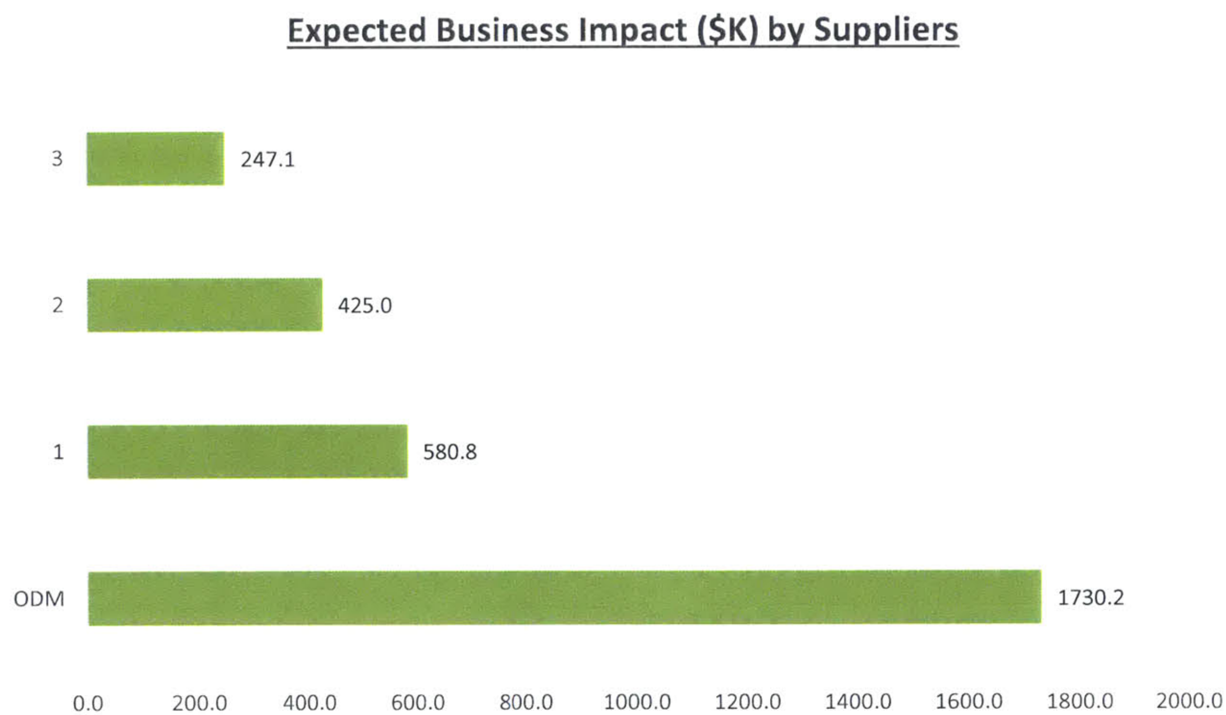

Figure 33 - Expected Business Impact aggregated by suppliers

Among the non-ODM suppliers, supplier 1 has the highest expected BI. This is because they have 2 facilities together contributing nearly 50% of total ODM volume. The more concentrated our supply base is, the more concentrated the risk is in the supply chain, since the failure of a single supplier could result in larger losses. One way to decrease the expected BI can would be to decrease the Blackout Period (BOP) or the Backup Period (BUP). In this case, decreasing the BOP would mean reducing the probability of bankruptcy of the supplier by transparency that comes from establishing a close working relationship with the supplier.

6.3.3 Assessing Locations

The resiliency of a location (city) is measured by the expected business impact of losing all facilities in that city. When an entire city is disrupted, we have all the nodes that represent the different processes and facilities in each facility of all suppliers in that city being disrupted simultaneously. Such an outcome is possible, for example, when the disruptive event is an earthquake or a Tsunami or a flood, such as the Thailand Floods of 2011.

For the ODM location, we have the following computations:

FACILITY - ODM Location A	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	1281.16	92.53	1373.69
MAJOR	343.17	13.35	356.51
Mg - ODM - Kunshan	1624.33	105.87	1730.20

+

FACILITY - Supplier 2 Location A	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	0.00	198.40	198.40
MAJOR	4.75	35.09	39.84
Mg - Fuyu - Kunshan	4.75	233.49	238.24

=

LOCATION	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
minor	1281.16	290.92	1572.09
MAJOR	343.17	48.44	391.61
	1624.33	339.36	1963.69

Figure 34 – Expected Business Impact for suppliers at location A

Exp. CaR (Location A) = MAX [Exp CaR (ODM, supplier 2 – Location A)]

= MAX[1624.3K, 4.75K] = 1624.3K USD

Exp. CtR (Location A) = SUM [Exp CtR (ODM, supplier 2 – Location A)]

= 105.9K + 233.5K = 339.4K USD

Exp. BI (Location A) = Exp. CaR (Location A) + Exp. CtR (Location A)

= 1624.3K + 339.4K = 1963.7K USD (due to rounding)

When we compute this for all locations in the commodity supply chain, we arrive at figure 35:

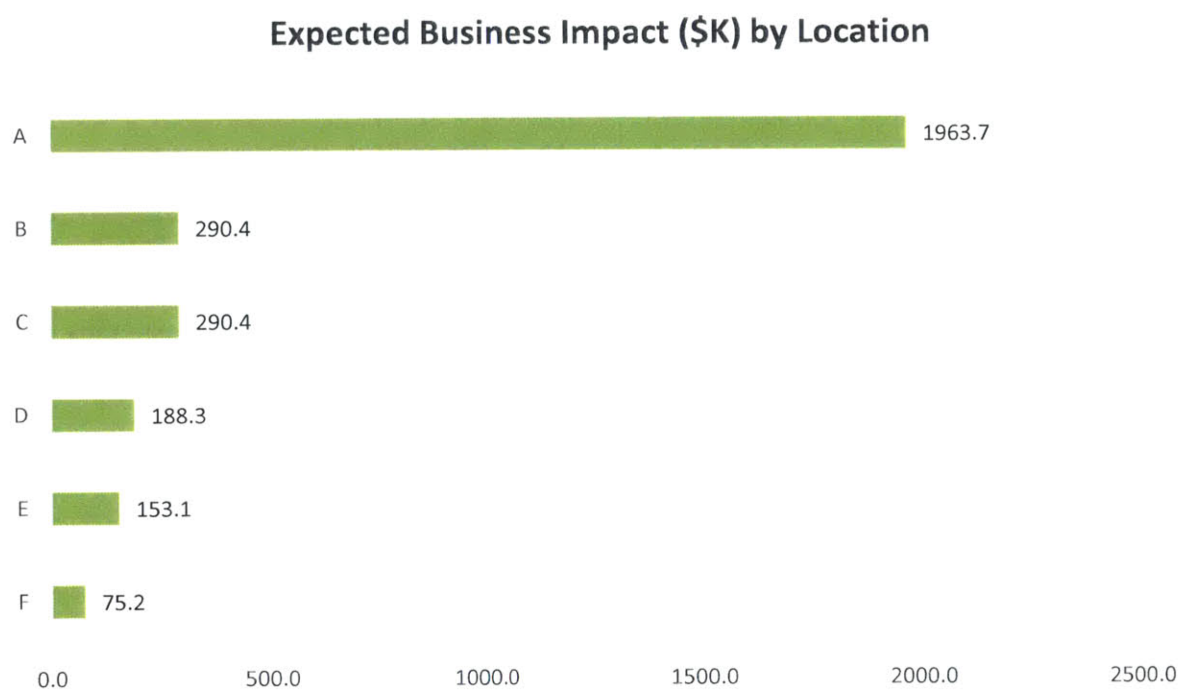

Figure 35 – Expected Business Impact aggregated by location

Of all the locations, location A has by far the highest expected BI. This is because there are 2 facilities, the ODM itself and a facility of supplier 2, in the same city. If this city has a high probability of major disruptive events (the kind that affects entire cities at a time), then it might be a better practice to use a different supplier facility to reduce the expected BI exposure.

6.4 Using the expected BI for Resiliency Mitigation Planning

One of the major objectives of resiliency assessment is to plan for mitigation. Planning for mitigation involves knowing where to invest mitigation dollars, how much to invest, and which mitigation option to invest in. The approach to doing this is similar irrespective of whether we are analyzing nodes, or facilities, or suppliers, or locations. Therefore we explain the process using Facilities as an example, but the same approach applies at other levels as well.

6.4.1 Where to invest mitigation dollars

Once we have a list of facilities with their corresponding expected BIs, we can rank them in descending order of expected BI to identify the top risky facilities.

FACILITY	Exp. CaR ($K)	Exp. CtR ($K)	Exp. BI ($K)
ODM	1624.3	105.9	1730.2
1A	3.8	286.6	290.4
1B	3.8	286.6	290.4
2 - Route 2	4.7	233.5	238.2
2 - Route 1	1.5	186.8	188.3
3 - Route 3	2.7	150.4	153.1
3 - Route 2	0.0	75.2	75.2
3 - Route 1	0	38	38

Figure 36 – Expected Business Impact for facilities sorted by business impact

In our case, the top risky facilities are ODM, supplier facility 1A, supplier facility 1B, and this is a useful starting point to conduct the next set of analyses.

For the critical nodes, we generate the response curves in section 5.6. The response curves tell us which node has the highest reduction in Exp. BI for the first dollar spent on mitigation, and we should invest first in that node.

6.4.2 How much (mitigation dollars) to invest

Based on the response curves in section 5.6, the optimal allocation of a budget of mitigation dollars would be such that the entire budget is spent such that the last dollar spent at each node has the same marginal mitigation utility.

6.4.3 Choice of Mitigation Option

The expected BI model functions as a quantitative assessment of resiliency calculator. Using this, one can simulate various mitigation options available to a company such as reducing the t(ASP) of an alternate supplier or having a second source or reducing the TTR of a node. This could potentially help the company evaluate the relative benefits of each option and choose the most effective one.

7. CONCLUSION

7.1 Results and Insights

The purpose of this research was to develop a composite framework for assessing supply network resiliency. Using our Balanced Scorecard of Resiliency (BSR) assessment approach, we successfully conducted a partial supply network resiliency assessment for one commodity for ABC Company. We were able to visualize the expected business impact risk for one commodity for ABC Company in both a map view and supply network view. Further, we aggregated the expected business impacts for ABC Company's supply chain by facilities, suppliers and locations in order to identify the riskiest entities in the supply chain. Lastly, we generated response curves for key parameters such as downstream inventory, and probability of occurrence of major and minor events for the riskiest entities.

The overall expected business impact of the disruption of the supply for one commodity for ABC Company is $2,968K. By facilities, the ODM facility has the highest expected business impact of $1,730K. ODM's expected business impact is highest because we did not consider ODM inventory in our calculation per ABC Company. Facilities 1A and 1B in figure 22 have the second highest expected business impact of $290.4K. Among locations, location A in figure 23 has the highest expected business impact of $1963.7K. Location A has the highest expected impact because of the proximity of two facilities in that area. Among suppliers, the ODM has the highest expected business impact of $1,730.2K. Supplier 1 has the second highest expected business impact of $580.8K. For the ODM facility, the marginal benefit of each additional day of inventory is around $200K, up to 7 days of inventory. Therefore, if the cost of deploying the additional day of inventory is less than $200K, ABC Company should pursue that mitigation option.

Our assessment allowed us to gain insights into the expected business impact risk for ABC Company under disruption. From our results, we gathered five main insights for ABC Company:

1. Tension is present between efficiency and risk. The leaner and more "procurement cost optimized" the supply chain is, the less resilient it may become. The strategy here would be to identify the sweet spot between efficiency and risk.

2. Assessing resiliency across the network allows ABC Company to prioritize mitigation dollars to the right facility and supplier, while providing the tradeoff between mitigation dollar and reduction in risk.

3. Visualizing supply chain risk helps managers understand the proximity of risk. Risk aggregates across nodes when the same facility, same supplier or same location occurs multiple times in a supply chain. For example, Supplier 1 has $580.8K (19.5%), and location A has $1963.7K (66.3%) of risk.

4. Risk at a node depends on Time-To-Recovery (TTR), Time-To-Blackout (TTB), inventory, and supply chain structure. Single source nodes pose higher risk, irrespective of value of component purchased.

5. Investing in mitigation options such as deploying additional inventory, reducing Time-To-Recovery (TTR), reducing Time-To-Blackout (TTB), or increasing supplier footprint can mitigate risk. The choice of mitigation option, and extent of investment depends on

the marginal benefit of the option v. the additional cost involved from the response curves

7.2 Future Research

While we have generated the supply network view of the expected business impacts for one commodity for ABC Company with our BSR method, developed a map-view, and generated insights from our findings, we have not conducted the qualitative SCRLC Supply Chain Risk Management Maturity Model assessment for ABC Company. The qualitative assessment may yield some other insights that will supplement our insights for ABC Company. Also, there are other resiliency assessments available in literature such as assessing parts, which could potentially be incorporated into the Balanced Scorecard of Resiliency approach. Our vision is to streamline our BSR methodology so it can be used as a comprehensive framework for assessing supply network resiliency.

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