

# Study of Supply Chain Disruptions at a High Tech Corporation

by

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Submitted to the Engineering Systems Division in Partial Fulfillment of the  
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## **Abstract**

Although supply chain disruptions are inevitable, frameworks have been developed for addressing supply chain risks. These frameworks present methods on mitigating, reducing or managing the risks through different approaches such as multiple sourcing. The research presented here identified two factors that contribute to successful recovery from supply chain disruptions. One factor is efficient communication between stakeholders in a supply chain. The communication needs to be present before a disruption occurs to enable fast detection. After a disruption occurs efficient communications will help minimize confusion and provide clear understanding of the recovery effort between stakeholders. The other factor is the inventory position downstream of the disruption. In particular, the available days of supply downstream from the disruption relative to the length of the disruption are crucial to the ability of a supply chain to recover from the disruption without disturbing the continuity of supply.

In response to the effect of the days of supply compared to the recovery time a simple model is developed for assessing supply chain risk for an enterprise that sells products defined through a bill-of-materials. The model takes into consideration the complexity of a product as more parts and more levels are added to the bill of material. The supply chain risk score metric permits comparison across products, companies and industries. The model is simple to apply by analyzing each part in bill-of-materials by a ranking system comparing the recovery time to the days of supply downstream from the disruption. The supply chain risk score is to be used in parallel with other supply chain metrics in order to determine the best approach in reducing risks to an enterprise.

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This journey, that brought me to MIT, was shaped in large part by my experiences at EMC. In particular, I would like to thank my managers Mark Macleod and Paul Callahan for guiding me through new roads. I am thankful to my colleagues for teaching me about new products, supply chain management and failure analysis. I would like to thank Jeff and Alison Leblanc for the strong friendship, support and all the discussions we've had over the years. They have been invaluable friends for five years in Providence. I would also like to thank the employees at HighTech I had an opportunity to work with on this Thesis. Their insight into supply chain risk management and feedback on the Supply Chain Risk Score model has been invaluable.

Lastly I would like to thank my parents Helen and Augustine and my brother John for encouraging and supporting me on this long journey. Without them by my side this would have been a much tougher journey.



# Dedication

This Thesis is dedicated to my parents Helen and Augustine and to my brother John,  
for their support, encouragement and confidence.



# Biographical Note

Theodore (Theo) Doucakis was born and raised in Athens, Greece. Upon completing secondary education at the American Community Schools of Athens in 1992 he matriculated at Brown University in Providence, Rhode Island. At Brown he pursued studies in Materials Science and Engineering. He was awarded a Bachelor of Science with Honors in 1996 for his work on Iron Aluminides under the guidance of Prof. Sharvan. K. Kumar. He continued his studies at Brown University in the field of Materials Science pursuing a Master of Science degree. During a two year leave of absence, from 1998 to 1999, he completed military service in the Hellenic Navy. Upon return to Brown in 2000 he submitted his thesis and graduated in May of 2000. After graduation he worked at EMC Corporation in Franklin MA starting as a failure analysis engineer. He soon moved to a supplier engineer role for new product introductions supporting EMC's midrange hardware product suite. In May 2006, he left EMC to enjoy some time with his family in Greece, before pursuing a Master of Engineering degree in Logistics with a focus on supply chain management at MIT in August 2006.



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# 1 Introduction

Recent events such as the 9/11 attack and the Katrina-Rita-Wilma hurricanes have heightened companies' interest in business continuity planning, which includes addressing supply chain disruptions. The identification of risks in a supply chain is neither trivial nor uniform across industries, companies or even product families. Researchers have developed frameworks to manage supply chain risks. Supply chain risk factors can be internal to the supply chain such as production quality, transportation and cost. External factors to the supply chain include labor strikes, natural disasters, political and economic changes. Supply chain risk assessment is an active area of research in academic literature. The supply chain risk assessment systems are either product focused or supplier focused. These risk assessment systems rely on the estimation of the probability of an event occurring in one of the external or internal risk factors and the subsequent monetary damage from the event to assess a risk. The estimation of the probabilities for a supply chain system of a large company in the retail, grocery or defense is an extremely large problem. Hence, this thesis explores a way to measure and quantify supply chain risk without considering the probabilities of disruptions.

The estimation of risk within a supply chain is of interest not only to businesses for their Business Continuity Planning but also for insurers that underwrite policies.

Ericsson filed a claim of \$200M that was covered by insurers. Following the disaster Ericsson developed a supply chain risk management framework that was accepted by its insurers and helped reduce premiums (Norrman & Jansson, 2004).

In order to gain an understanding of the problem of recovery from supply chain disruptions the efforts of a high tech company are documented. The company, called here HighTech to protect its identity, is active in the Information Technology arena, producing hardware and software. One internal disruption was caused by a quality issue affecting tens of thousands of items while the other, external, disruption was the loss of a supplier due to financial difficulties. HighTech provided access to its supply chain and manufacturing organizations in order to learn about supply chain risk as it pertains to its operations. The insights gained from this study motivated the development of a model for supply chain risk assessment. A preliminary exploration of the model is presented together with some of its pros and cons. The thesis concludes with recommendations and conclusions drawn from the case studies and the proposed model.

# 2 Literature Review

Since the events of September 11<sup>th</sup>, 2001 increased efforts have been placed on better understanding and measuring supply chain risk. Research into supply chain risk assessment and management has flourished as supply chains have extended around the world. The span of supply chains has increased their vulnerability to exposure from dangers both internal and external. Zsidisin et al. (2004) reviews current supply chain risk assessment techniques and concludes that purchasing organizations need to take a proactive approach to supply risk assessment in order to best understand the impact of disruptions on inbound supplies. Furthermore, supply risk may be assessed as part of other management tools such as supplier qualification audits and performance improvement efforts with suppliers. Pai, et. al, (2003) propose the use of a hybrid of Bayesian networks and fuzzy logic to evaluate risk in supply chains. However the model is constrained by the amount of information necessary. In particular, for a node, with four parents and four discrete states, 4094 probabilities need to be assigned. Hence the authors realize the difficulty in using such a model in a practical application.

Researchers at the University of Cranfield propose a structured method for determining the supply chain risk (Cranfield University, 2003). The process includes four steps starting with a description of the supply chains, then a vulnerability self assessment, followed by an evaluation of the implications and concluding with identifying actions. The process helps companies develop actions that address both

mitigation and contingency in case of supply chain disruptions. However the framework is based on company expertise and insight rather than an independent assessment system.

One of the most well documented supply chain disruptions resulting in substantial loss of revenue and market share has been that of Ericsson, Sweden, due to a fire at a sub-contractor plant in Albuquerque, New Mexico (Wall Street Journal, 2001). Following that disaster Ericsson developed and implemented a proactive supply chain risk management approach (Norrman & Jansson, 2004). The process includes a risk identification process where components and services to Ericsson are mapped through the first and second tier suppliers and are classified by the number and type of sourcing such as single-sourced vs. multi-sourced part. The next step identifies the “business recovery time” (BRT) depending on how quickly deliveries can return to pre-disruption levels by use of an alternative source. The risk assessment process comes next for which Ericsson has developed an internal tool that takes into consideration the business processes, the financial health and the business continuity planning at the supplier.

Additional information used in assessing risk is the natural and man-made hazards of the supplier site such as earthquakes and electricity shortages. Ericsson does not use the customary “risk value” (impact x probability) due to the difficulties in attaining reasonable numbers for probability as well as impact. Instead Ericsson uses internal resources to determine the Business Interruption Value (BIV) that is a product of the gross margin and the business recovery time. This results in categorizing different disruptions in a 4x4 matrix of probability and consequence as seen below in Table 1.

Table 1 Template for risk assessment

		Consequence			
		Negligible	Minor	Major	Severe
Probability	Almost certain	MEDIUM	HIGH	VERY HIGH	VERY HIGH
	Likely	MEDIUM	HIGH	HIGH	VERY HIGH
	Unlikely	LOW	MEDIUM	HIGH	HIGH
	Rare	LOW	LOW	MEDIUM	HIGH
(Norrman & Jansson, 2004)					

It is interesting to note that Ericsson treats as equivalents events with rare probability and severe consequence and an almost certain event with minor consequences, both are high. The risk levels from very high to low require different actions as indicated in Table 2 . The template for the risk assessment is arbitrary.

Table 2 Template for risk treatment and contingency planning

Degree of Risk	Risk Level	Action Required
VERY HIGH	Red	Risk mitigation required to level medium or low. If the risk is not mitigated monitoring and making a contingency plan is required
HIGH	Orange	Risk mitigation required to level medium or low. If the risk is not mitigated monitoring and making a contingency plan is required
MEDIUM	Yellow	Risk mitigation required to level low is optional, monitoring is required
LOW	Green	No further risk mitigation is required
(Norrman & Jansson, 2004)		

The risk management is followed with risk monitoring and follow-up so that risks can be reduced down to the next level and preferable to a low status. However, in cases where it is not possible to manage risk, contingency plans are created and documented. The mitigation strategies and costs associated with them are compared to the business interruption value.

Kim et al. (2004) in a study that simulates supply chain robustness defines the supply chain cycle time resilience ratio, SCR, as:

$$\text{SCR} = \frac{\text{Supply Chain cycle time under variation}}{\text{Normal supply chain cycle time}} \quad (1)$$

This ratio indicates a resilient supply chain when the ratio is close to 1 and a non-resilient supply chain when the ratio is much larger than 1, implying a supply chain cycle time under variation or disruption significantly larger than the normal cycle time. No further information was located on the use of this resilience index.

Dong (2006) proposes the use of a robustness index based on the connectivity of each node as well as the accessibility of each node and link. The robustness index (RI) is not bound on the top end of the spectrum and is only dependant on the size of the network being analyzed. Although the index can be used internally within a company to try and increase the robustness index it is not possible to compare robustness indices across companies.

In summary, frameworks have been developed for estimating and managing supply chain risk towards reducing the risk level of a particular supply chain. These frameworks require estimation of all events that may cause a supply chain disruption thus making supply chain risk measurement cumbersome. Lastly, these frameworks cannot be applied across companies for comparison purposes between these companies much like Earnings per Share (EPS) is used by financial investors.

# 3 Two supply chain disruptions

HighTech is a publicly traded company active in the information technology sector. It provides hardware and software solutions through direct sales, partners and value add resellers depending on the market segment. The company has been in existence since the late 1970's and has grown organically and through acquisitions over its lifetime becoming a leader in its sector. In recent years its focus has been shifting towards software and services because hardware is increasingly commoditized while profit margins decrease. HighTech provided access to its supply chain and manufacturing organizations for an analysis of supply chain risk drivers and disruption management. A HighTech organizational chart with the main groups can be seen in Figure 1.

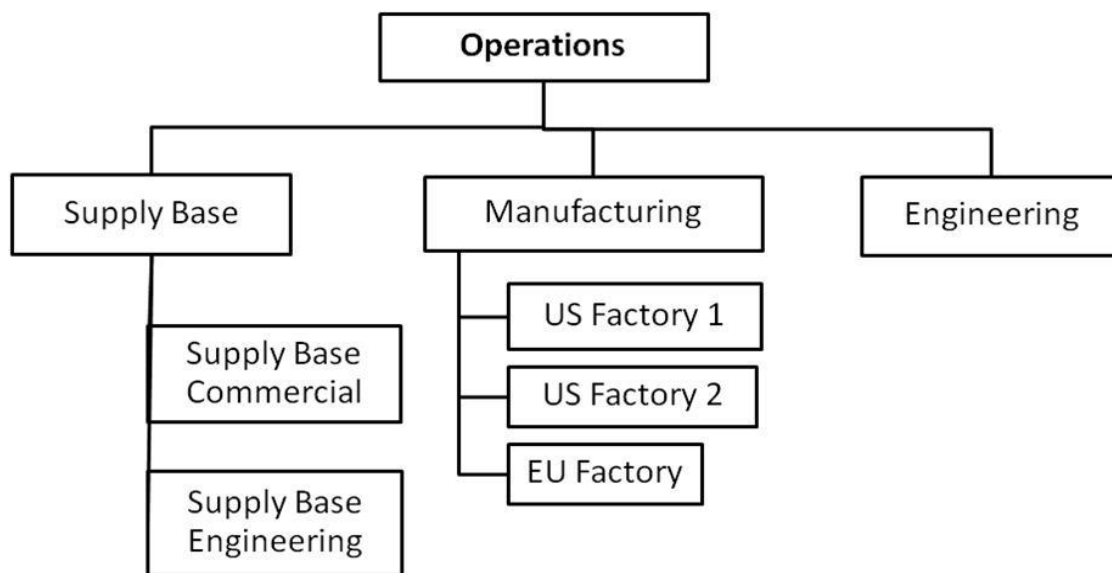


Figure 1 HighTech Hardware Operations Organization

HighTech's supply chain organization is focused on the inbound flow of material into manufacturing sites. Three manufacturing sites are located in the US and Europe, serving customers in their respective geographical areas. The US manufacturing sites serve the North and South American markets, while the European site serves the European, Middle East, Africa and Asia-Pacific markets (Figure 2). The manufacturing sites are in essence final assembly test and configuration sites. The main hardware components are sourced from contract manufacturers and suppliers across the globe, primarily from low cost geographies such as Mexico, Eastern Europe and Southeast Asia (Figure 3).



Figure 2 Distribution network



Figure 3 Supply network

The supply base organization is tasked with managing the supplier relations in all of these geographies. The supply base organization is based in the US with presence in all three manufacturing locations. Furthermore, efforts are underway to place resources close to the current suppliers in low cost regions in Southeast Asia and Mexico. The organization is responsible for qualifying a supplier through a review process that can last from one month to one year depending on the nature and criticality of the product the supplier will be providing. The qualification process includes a technical and financial assessment. The technical assessment covers all manufacturing areas of the supplier starting from incoming material, progressing through production and test and concluding with shipment and management of returned material. The audit focuses on the processes, the quality audits and the management of defective material by the supplier. Similarly the financial assessment focuses on the financial health and

the transaction handlings of the candidate supplier. Suppliers who provide critical components that can directly impact customer experience are qualified under stringent requirements including margin testing at the high and low extremes of operating conditions, such as temperature, voltage, electromagnetic interference and vibration. This extensive testing is time and resource consuming and needs to be balanced with the needs for current product support as well as product development efforts.

Following qualification of a supplier or new product the supply chain organization is responsible for monitoring and managing the quality of the incoming material and implementing corrective actions. However, when defective material enters the three factories a purge process document is used to communicate required actions to the manufacturing organization. The purge usually requires manufacturing to quarantine the defective or suspect material and either dispose of it as non salvageable or repair it, in-house or externally, before returning to the manufacturing process.

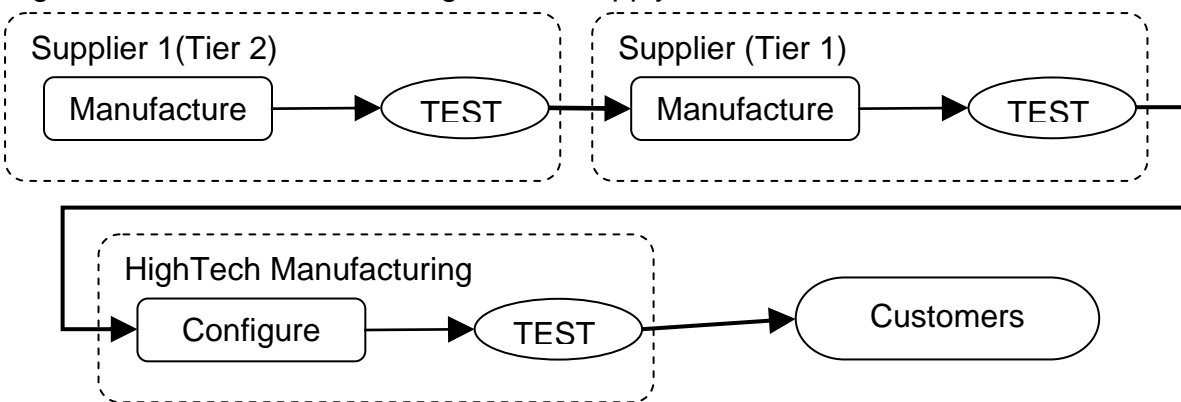
### ***3.1 Part quality issue***

Quality issues that result in purges are major disruptions in the operations of HighTech. A purge is a process by which defective material or material suspect of defects is removed from the manufacturing process. The material may be disposed of or repaired and returned to the manufacturing process depending on the issue. Purges are seen as necessity in order to protect the user experience and the firm's product, image and reputation. Hence great efforts are taken to execute purges as rapidly and efficiently as possible. The quality issues that result in purges are usually detected within the three manufacturing locations. However it is often the case that not all sites

are impacted, depending on material flow. Purges are also reviewed by a cross-organizational board to decide on the necessity for a product recall impacting material that is downstream of the manufacturing sites either in the field spares or installed at customer locations.

Product quality is ensured through design, manufacturing and test practices. The defect detection strategy for each component and sub-assembly is a layered approach with ever increasing and complementary levels of detection as material flows through the assembly process, both externally at the suppliers and internally at the three sites of HighTech. At the suppliers' locations components are inspected to varying levels; however the defect detection at any one stage before the final test and configuration at the three manufacturing sites is not exhaustive. HighTech selects to limit subcontractors' ability to test due to intellectual property concerns. As a result, quality issues may go undetected at the subcontractors. Thus, most quality issues that result in a purge are detected during product testing within HighTech's manufacturing. Another possibility is for a supplier to inform HighTech supplier engineers of the existence of a lot of suspect product that has already shipped from the supplier and is downstream from them in the supply chain.

Figure 4 Material flow within HighTech's supply chain



When HighTech's technicians detect a failure they inform HighTech's supplier engineer responsible for that particular commodity to jointly or solely determine the root-cause of the failure. The supplier engineer is responsible for the quality of incoming material from their supplier(s) and will take action with any failure found on the manufacturing floor. If a trend is identified either by the supplier engineer, manufacturing quality control or the supplier then a discussion will start between the supplier engineer and quality control on the need for a purge.

The purge is a major event for the corporation's manufacturing sites and the supply chain organization as it disrupts the smooth flow of product and operations. It is intended to stop the flow of defective or questionable material from leaving the factories and reaching the customers. The purge is documented within the electronic product lifecycle management (PLM) system. The document describes the nature of the quality issue and the extent of exposure. The part numbers of effected assemblies are entered into the PLM system together with the serial number list or other genealogical information. The purge is subsequently disseminated electronically for approval by the manufacturing, supply base and engineering organizations. Upon approval of the purge, the PLM group uploads the effected serial number lists into the ERP system for tracking, disposition and clearance.

At this point the purge is active and execution begins. The execution steps have been predetermined during the approval process. Steps may include inspection and repair or return to vendor or any number of other combinations. The ERP system controls the flow of discrepant material throughout the factory based on "flags" that have been set. Hence any material transaction will be checked against the active purge

serial number list. Each assembly, as it moves within the factory, is tracked in the ERP system where quality information is entered after each test and nesting information is entered as subassemblies are added. If any subassembly, within the transacted assembly, is flagged for a purge the transaction will stop until the effected subassembly is cleared. This can mean the stoppage of material flow throughout the production process.

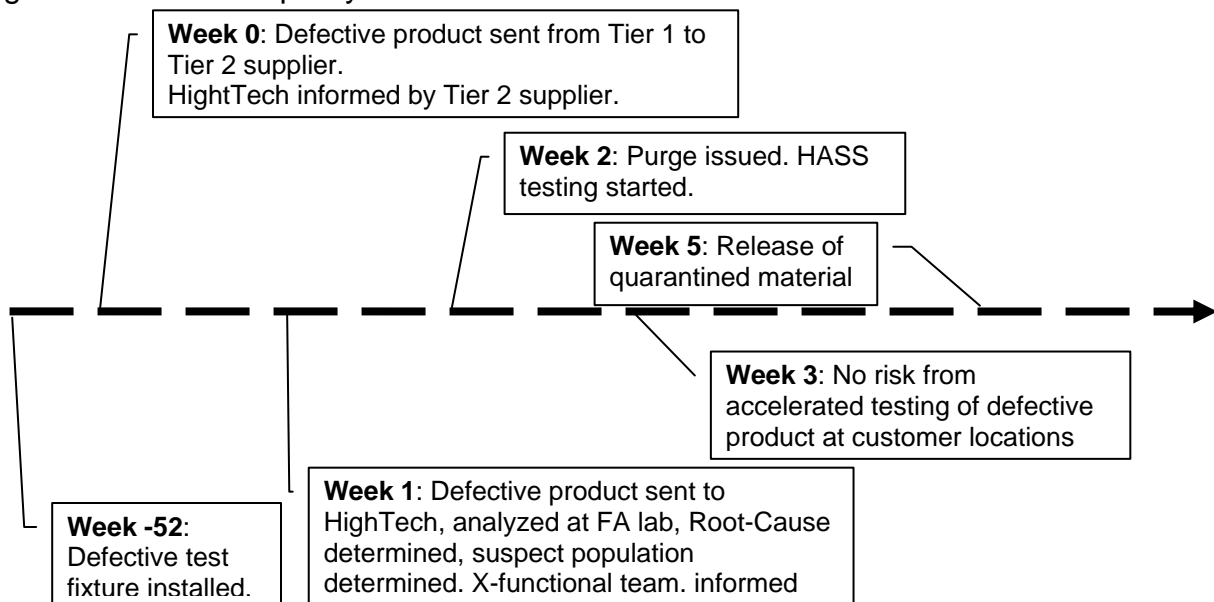
Once an item that is on the purge serial number list is detected, the purge process may require an inspection and return to manufacturing operations, repair or replacement depending on the nature of the quality defect. The purge document will specify the nature of activities as well as the retest process if an assembly needs to be taken apart or an item repaired. This discovery, repair and retest can be very time consuming as the test process can exceed three to four days for some products.

The current process requires that supplier engineers authoring purges impacting production material complete a World Wide Purge Costing model spreadsheet. The intention of this model is to capture the costs associated with executing this purge. The model captures labor, material, equipment and transportation costs associated with returning impacted material to production. However the model does not capture costs such as impact to deliveries and development schedules or inventory costs associated with the material being purged.

The following is an example of a quality purge that impacted operations recently. The event started unraveling when a Tier 1 supplier sent product back to a Tier 2 supplier for failure analysis as some of the product was failing during final test at the factory of the Tier 1 supplier. The transfer of material was for seven to eight defective

units, a small fraction of the total material manufactured by the Tier 1 supplier. The transfer occurred towards the end of the financial quarter as suppliers try to minimize inventories in their factories by shipping products to the customers and failed components to suppliers for failure analysis. A timeline of the events can be seen in Figure 5.

Figure 5 Timeline of quality issue



The Tier 2 supplier, upon receipt of the defective material, started to pursue root-cause analysis. At this time the Tier 2 supplier informed the HighTech supplier engineer of receiving this defective material as part of the weekly quality call where issues with production are discussed between the supplier and the HighTech engineer. The supplier engineer then proceeded to drive the resolution of this issue. Within a couple of days the Tier 2 supplier determined that the defect was not caused by their manufacturing process and informed the supplier engineer at HighTech of this result. The failure analysis lab at HighTech came to the same conclusion by analyzing product

at HighTech's factory from the same vintage as the failures. However the lab staff had a further insight to the cause of the defect.

The lab staff, in cooperation with the supplier engineer, noticed that the defect had the signature marks of a test process. The next step was to engage the test engineering team at HighTech that is responsible of developing all test applications and test processes for this type of product. The test engineers quickly realized what was causing the defect was a design error in the test process. The test engineers assisted the lab engineers in replicating the defect on known good product. The supply base manager responsible for this product informed the cross functional team responsible for monitoring the production quality within HighTech.

The cross functional team consists of managers from engineering, manufacturing, supply base management, procurement and logistics. The team is tasked with addressing any issues that could impact production within HighTech's plants and meets weekly. The team was informed of the current state and understanding of the problem and the steps to follow. Hence, within four days of the Tier 2 supplier first alerting HighTech of the returned product the root-cause of the defect had been identified and the stakeholders within HighTech were aware of the developing situation.

The next step taken by HighTech was to understand the population of product suspect of being defective within manufacturing, engineering labs and customer locations. The test engineers in collaboration with the Tier 1 supplier and the supplier engineer responsible for the Tier 1 supplier were able to understand the magnitude of

the problem. The issue was caused by a wrongly built test fixture that was in use at the Tier 1 supplier from a very early stage in the lifecycle of the product.

As the end of the second week approached, the Tier 1 supplier provided a serial number list for all suspect product and it soon became evident that all material currently at HighTech as well as material at customers of HighTech was suspect for this defect. The large population of suspect product and in particular the existence of suspect product in the field caused HighTech to pursue further testing while a Purge was issued to quarantine product in-house. So by the third week, since first finding out about the shipment of defective material from the Tier 1 to the Tier 2 suppliers, the root-cause had been determined and a purge was issued.

The purge document requested HighTech manufacturing to inspect a large population of product, in the tens of thousands, and segregate the worst case conditions based on guidelines provided by the failure analysis lab. The failure analysis lab in coordination with manufacturing performed destructive analysis and characterization of worst case conditions of the defect as well as Highly Accelerated Stress Screening (HASS). The results from these tests provided crucial information to HighTech for the behavior and reliability of product. It became evident that product which had not failed during the test processes, at the Tier 1 supplier or HighTech, would not fail in the field, at a customer. However, a repair procedure was instituted at HighTech for all in-house material in an effort to minimize risks. As the inspection progressed it became evident that only 10% of the suspect product required repair. This low impact coupled with the ability to repair did not require the ordering of material to cover shortages. However,

procurement was preparing Tier 1 suppliers to expedite new product builds in order to minimize impact to the deliveries to HighTech customers.

In discussions with the supplier engineers, test engineers and manufacturing engineers as well as procurement at HighTech there were some recurring themes that highlighted the ability of HighTech to respond to this disruption. The main one is communication. As soon as the supplier engineer was first informed by the Tier 2 supplier of the issue, communication within HighTech as well as across the supply chain was managed effectively. That meant stakeholders were provided with the necessary information to make decisions or be aware of decisions being made. The existence of the cross-functional team enabled the dissemination of information and status update to many number of stakeholders but minimized confusion and different message paths. Two other related factors are the technology enablers of the in-house failure analysis lab and the quality control (QC) system within HighTech. The in-house lab, having very good familiarity with the product and the manufacturing process, was able to rapidly determine the root-cause. The quality control system within HighTech enabled supplier engineers to quickly get a picture of where material was located physically. The QC system enabled engineers to trace all suspect material for any related events that could provide evidence for this defect. One area where HighTech felt improvement was necessary was in the monitoring of suppliers for defects. In particular the yields for this product were very high, above 98% and the defects in general are minor. However HighTech management believes the severity of this particular defect when detected at the Tier 1 supplier should have caused a more focused response by the supplier and the alerting of HighTech to the issue.

The rapid and successful recovery from the quality issue can be attributed to a number of factors. The rapid identification of the root-cause of the defect and extent of exposure enabled the manufacturing operations to repair material progressing through the test process. The nonexistent risk from material at customers allowed HighTech to focus resources to in-house material only. The presence of sufficient inventory within the test process at HighTech allowed the manufacturing process to continue while the defective inventory was being purged and repaired.

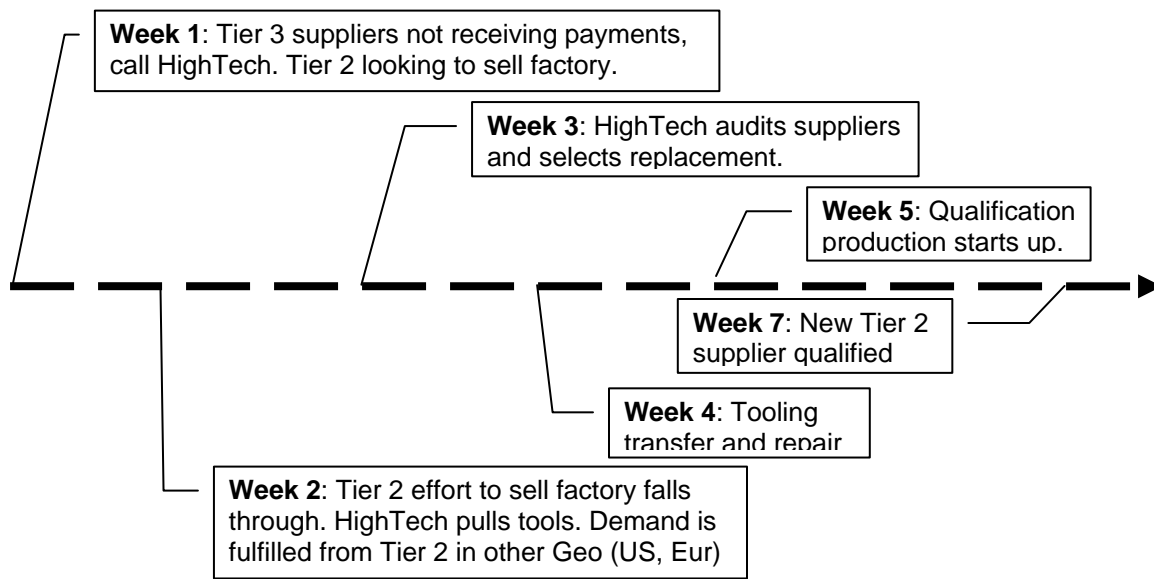
### ***3.2 Loss of supplier***

HighTech manufacturing is faced with a couple of purges each quarter due to supplier issues. Hence the supply base and manufacturing organizations have learned how to best minimize disruptions. On the other hand, the loss of a supplier due to financial reasons or other catastrophic event is a very infrequent event for which HighTech does not have a process guiding the recovery. The loss of a supplier, unlike the quality issues, usually impacts many part numbers that the supplier provides. HighTech was recently faced with the loss of a Tier 2 supplier (called here SheetMetal Inc.) with operations in Eastern Europe. SheetMetal Inc. fed a Tier 1 supplier who in turn supported the European manufacturing site of HighTech. SheetMetal Inc. is active in an industry characterized by low margins and high capital investments. Although SheetMetal has been a supplier to HighTech for the last four – five years it went into Chapter 11 bankruptcy in 2002 and reemerged in two months later after restructuring. As the supply base strategic manager said “sheet metal stamping (manufacturers) are on the edge (of bankruptcy) because it’s tough to make money”. The manager

mentioned that every couple of months there is a new rumor in the industry that one of the stamping suppliers is facing hardship and could be going under. The manager usually investigates these rumors by calling the supplier, asking for information and financial statements to assess the health of the supplier. Other means used to assess the financial health are reports from Dun & Bradstreet, industry news feeds and other suppliers.

In early 2007, Tier 3 suppliers, providing material to SheetMetal, called the supplier manager at HighTech asking for assistance in receiving payment for goods provided. SheetMetal was more than 30 days late on payments for goods received. The supplier manager, realizing that SheetMetal may be in financial trouble, called his contacts at the company. The executive vice president of the Eastern European factory of SheetMetal responded that there are indeed challenges and SheetMetal was looking for a buyer for the factory and all would be resolved within a week. A timeline of the events as they unfolded is seen in Figure 6.

Figure 6 Timeline of supplier loss



When the HighTech supplier manager tried to call again a week later he could not reach any of the contacts. The EVP at SheetMetal called back the following day stating that the effort to sell the factory was not successful and SheetMetal was exploring other options. The HighTech supplier manager decided that the best course of action was to rapidly disengage with this supplier and try to recover the tooling from the factory as the financial troubles could rapidly escalate to insolvency for SheetMetal Inc.

As this decision was made a team of supplier managers, supplier engineers and Tier 1 representatives established a conference call to coordinate actions. The brunt of the work was executed by the HighTech personnel in the US and European manufacturing locations. The Tier 1 supplier provided recommendations for a new sheet metal supplier and HighTech sent supplier engagement teams to audit them as well as other options. The audits were executed based on standardized processes that include technical and financial operations assessment. One major concern before HighTech disengaged with SheetMetal was the removal of tooling from the SheetMetal factory as these are high value and long lead time assets. Hence, HighTech employees tagged all stamping dies at the SheetMetal factory and removed the tooling within three days of the decision to disengage. Last but not least, in order not to disrupt the continuity of supply other Tier 2 suppliers were asked to increase production to cover for the loss of SheetMetal. There was a price premium for this action as procurement costs were higher due to transportation but the continuity of supply was secured.

Three weeks after first indications of trouble at SheetMetal, HighTech had recovered the tooling and selected an alternate supplier to recover production. A short term solution was in place to satisfy demand with production from other Tier 2 suppliers. The long term solution, to bring up a new supplier location, was in process as the tooling was transferred to the new supplier by the fourth week. Qualification production started by the sixth week and two weeks later full production had resumed at the new Tier 2 supplier location.

The supplier manager at HighTech was quick to point out that the loss of SheetMetal, although sudden and disruptive happened at a very fortunate period. The parts supplied by SheetMetal were sourced at two other suppliers, one in Europe and one in the US thus ensuring redundant sources. Although there was a premium for transportation and cost, the demand could be satisfied by these two suppliers. The new supplier location selected was a Czech factory of an existing Tier 2 European supplier. This fact minimized the learning curve as the supplier was familiar with the product, processes and expectations of HighTech. Furthermore, the “new” supplier was willing to rapidly deploy resources from the current production location to the Czech factory to expedite ramp-up to production. Once again fast communications between the US and European operations of HighTech and the Tier 1 supplier contributed to the recovery. The team had a daily conference call to address any issues and two to three email updates through the day. The time difference between the US and Europe was used to rapidly complete tasks within an “extended work day” as tasks were handed off between each HighTech location during the conference call. Similarly to the quality issue, one additional enabler was the deep technical know-how at HighTech of the sheet metal

product, processing requirements and supplier capabilities. This know-how, in conjunction with a good understanding of the delivery requirements permitted the rapid and successful selection of a new manufacturing site and the proper scheduling of ramping of production.

Most importantly the Tier 1 supplier had all inventory of parts required to satisfy the demand for the quarter! The existence of this inventory within the supply chain allowed the continuity of supply. Similarly, for the quality purge described earlier, deliveries to customers were not disrupted as the inventory on hand permitted the smooth execution of the purge without disruption to the delivery schedule.

### ***3.3 Observations***

The two cases described provide some key factors that enabled HighTech to recover from the supply chain disruptions it faced. One factor is the importance of communication between the supply chain partners. In both cases HighTech received first indications of the disruption from suppliers upstream of where the disruption was occurring. HighTech is structured in such a way that it has close relations with suppliers upstream to the Tier 3 level and beyond for some parts. These relations serve well only when information flows freely between the supply chain members.

The second factor that contributed to the recovery was the communication between stakeholders once the disruption had occurred and was detected. HighTech has one main forum, a cross functional weekly meeting, for communicating issues that can impact production. The forum is attended by management from engineering, supply chain management and manufacturing. Similar meetings are held for each

manufacturing location due to minor differences in product mix. However, when an issue impacting multiple locations arises, then the meeting across manufacturing locations is consolidated so as to facilitate communication across all stakeholders. In the second case where the supplier in Europe was going out of business the coordination between the European and US supply chain organizations of HighTech was high thus enabling the quick recovery after the loss of the supplier.

The last factor that contributed to the rapid recovery and the lack of impact to customer deliveries was the presence of sufficient inventory at locations downstream from the disruption as to avoid loss of continuity in the supply. Thus, the days of supply downstream from a supply disruption is a critical factor when compared to the days to recovery from the disruption. This observation led to the development of the supply chain risk model discussed in chapter 4.

# 4 Supply Chain Risk model

## 4.1 *Supply Chain Risk Model development*

A review of current literature indicates that there is no universal metric for supply chain risk. Norrman and Jansson (2004) present the supply chain risk management framework used at the telecommunications manufacturer Ericsson. Supply chain risk managers were deployed within core units to manage and coordinate the optimal balance between risk exposure and risk mitigation. However the process is complex and does not transport to other companies or industries.

Hence the desire to develop a supply chain risk measurement system that can be applied uniformly across industries is strong. The model proposed herein is based on discussions with the personnel from HighTech and builds on concepts developed by Norrman and Jansson (2004). The current development of the model is based on a manufacturing based company that produces items internally or externally at sub-contractors.

The model assumes the company has a number of products that consist of Bill of Materials following general tree structure as show in Figure 7.

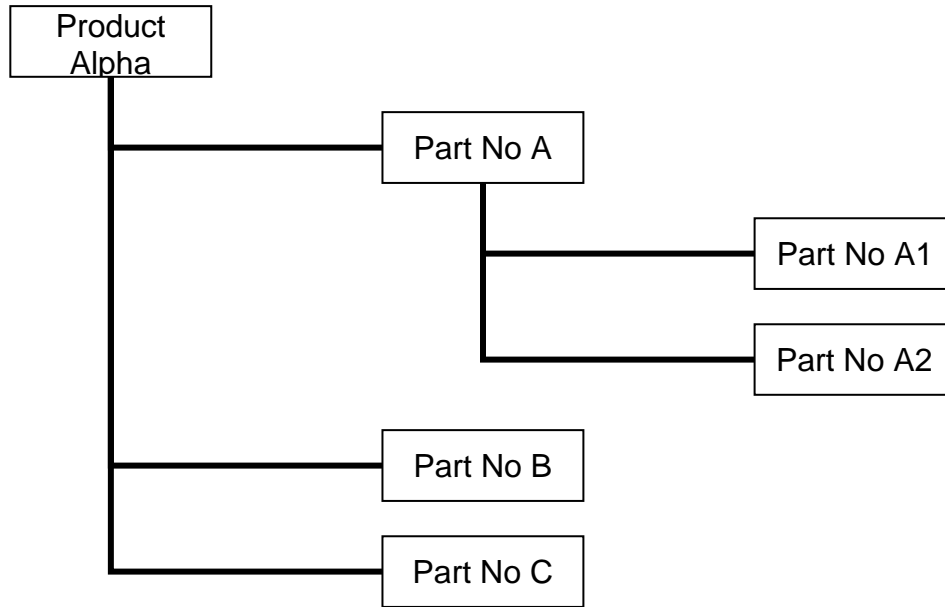


Figure 7 Product Bill of Materials

The model starts by the analysis of every part number in a bill of materials (BOM). Each part number is assigned a score from 1 to 4 based on the following criteria (Table 3):

Table 3 Supply Chain Risk Scale

Scale	Risk	Disruption event	Business Recovery Time (BRT)	Recovery plan available
4	None	Unnoticeable	Much less than days of supply	Yes
3	Low	Noticeable	Less than days of supply	Yes
2	Medium	Noticeable	More than days of supply	Yes
1	High	Noticeable	More than days of supply	No

The disruption event is any event that will stop the flow of the particular part number from the current source for an indefinite period of time. The Business Recovery Time (BRT) is defined as the days to return the supply of that part number to the pre-disruption level. The BRT is compared to the inventory days of supply<sup>1</sup> at the next level downstream in the supply chain or BOM. The underlying logic being that if the flow of

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<sup>1</sup> Inventory Days of Supply = Inventory on hand / Average daily consumption rate

parts is recovered before the on hand inventory is exhausted than the disruption in flow will not propagate further into the supply chain.

The next criterion is the existence of a recovery plan for the part number under analysis. The recovery plan needs to be well understood by the supply chain partners and easily referred to in case of a disruption.

Once each part number is ranked according to the above scale the aggregation by BOM level is performed. The aggregate, R, Supply Chain Risk Score ( $SCRS_L^R$ ) for a particular BOM level, L, is the harmonic mean of the level's part numbers:

$$SCRS_L^R = \frac{n}{\sum_{i=1}^n \frac{1}{x_i}} \quad (2)$$

Where:

SCRS: Supply Chain Risk Score

L: is the BOM level

R: aggregate

$x_i$ : is the rank of part number i.

n: are all the part numbers or stock keeping unit (SKU).

So that  $SCRS_4^R$  is the aggregate score for the 4<sup>th</sup> BOM level of a product

The next step is to aggregate the risk levels across the different BOM levels using the harmonic mean. This creates an aggregate risk level for a particular product, P,  $SCRS_P^R$ .

$$SCRS_P^R = \frac{\lambda}{\sum_{L=1}^{\lambda} \frac{1}{SCRS_L^R}} \quad (3)$$

Where:

$SCRS_P^R$ : is the aggregate Supply Chain Risk Score for a product, P.

$SCRS_L^R$ : is the aggregate Supply Chain Risk Score for each BOM level, L.

$\lambda$ : is the total number of BOM levels.

L: is the BOM level.

The use of a harmonic mean is preferred compared to the arithmetic mean because it weighs a low ranking part more heavily as seen in Table 4. Although all three cases have an arithmetic mean of 3.00, in the 3<sup>rd</sup> case the harmonic mean of 2.00 more accurately represents the criticality of having a high risk part with a score of 1 in the bill of materials.

Table 4 Comparison of means

	Part Score			Total	Arithmetic mean	Harmonic mean
1 <sup>st</sup> case	3	3	3	9	3.00	3.00
2 <sup>nd</sup> case	4	3	2	9	3.00	2.77
3 <sup>rd</sup> case	4	4	1	9	3.00	2.00

The existence of a high risk part number in a BOM is more critical and detrimental to the supply chain than having multiple low risk parts with risk scores of 3. Hence, the use of a harmonic mean is one way to overweight low scores and is easy to calculate in order to indicate this differentiation in the aggregation of the part number score up to the BOM level score and then to the product supply chain risk scores.

There are two extensions that are applied to the risk levels at the BOM level in an effort to address the complexity of a BOM. In particular the following assumptions are made:

1. Parts located at higher levels of a BOM, further away from the final product, are more risky.
2. More parts at a particular level of a BOM are more risky than less parts in same level.

The first assumption is based on the hypothesis that for a BOM with more levels, the product's supply chain becomes increasingly more complicated to manage due to decreasing visibility by the final customer. The second assumption is based on the hypothesis that management oversight and opportunities for disruption increase as more part numbers are added at a particular BOM level.

Hence a second set of supply chain risk metrics is created that scale the raw supply chain risk score by the effects of the BOM structure in both depth and breadth (number of parts at a level and number of BOM levels respectively). This scaling is accomplished by using two decaying factors, one for BOM depth and another for breadth. The complexity decay factor,  $r$ , can range from 0 to 1. The BOM decay factor,  $b$ , can range from 0 to 1. The relationship for scaling each level metric is:

$$SCRS_L^S = \frac{1}{L^b} \times \frac{1}{n^r} \times SCRS_L^R \quad (4)$$

Where:

$SCRS_L^S$  : is the scaled Supply Chain Risk Score for a particular BOM Level L.

L: is the BOM level.

b: is the BOM decay factor.

n: is the number of part numbers at the particular BOM level L.

r: is the complexity decay factor.

$SCRS_L^R$ : is the raw Supply Chain Risk Score for a particular BOM Level L

The BOM scaling factor as a function of the number of BOM levels and the decay factor b is showed in the graphs below (Figure 8 and Figure 9 ). The red line indicates the value of b (0.050) used in the models.

Figure 8 Scaled score vs. BOM decay factor ( $0 < b < 1$ ) for BOM levels 1 to 8

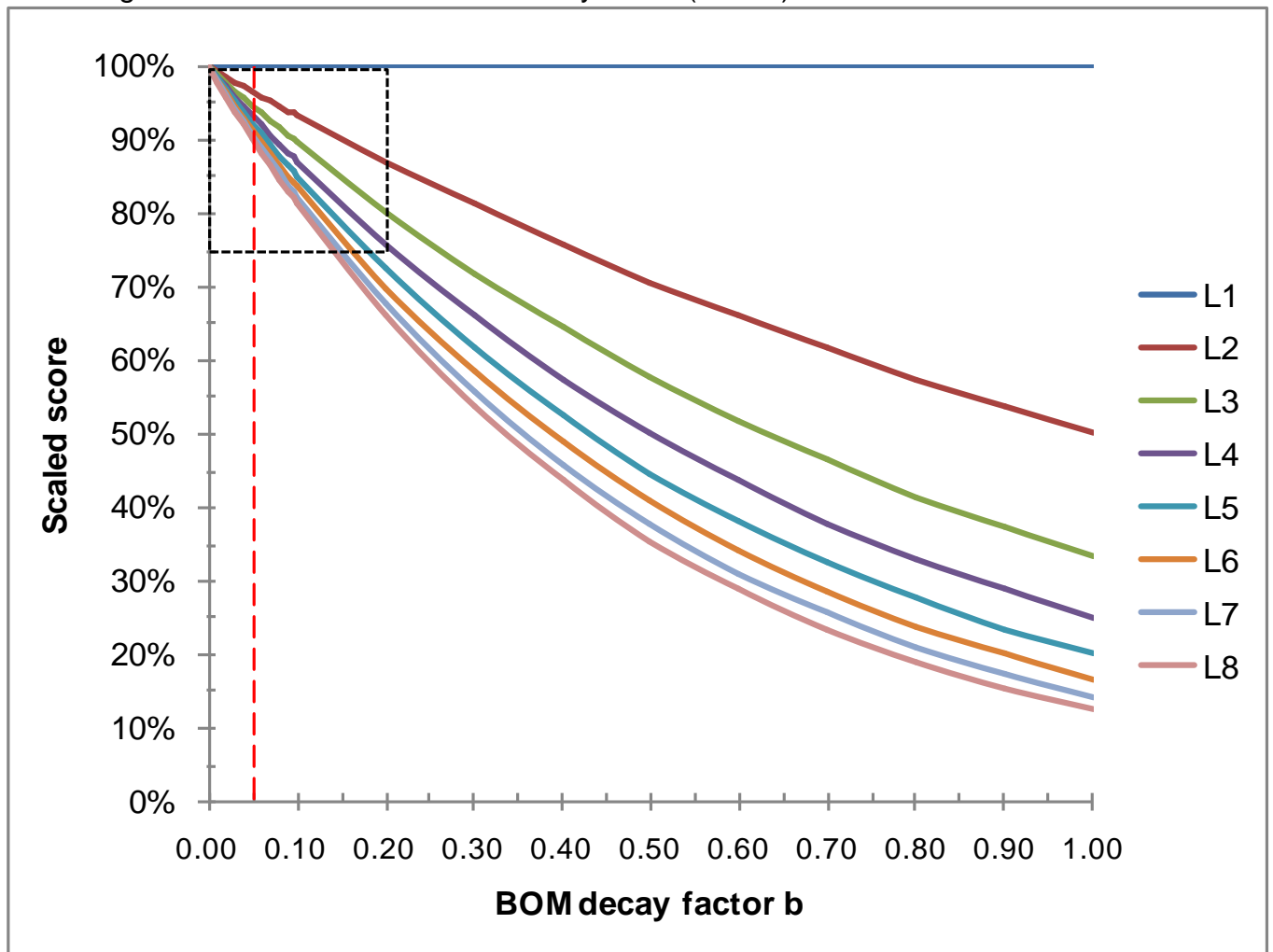
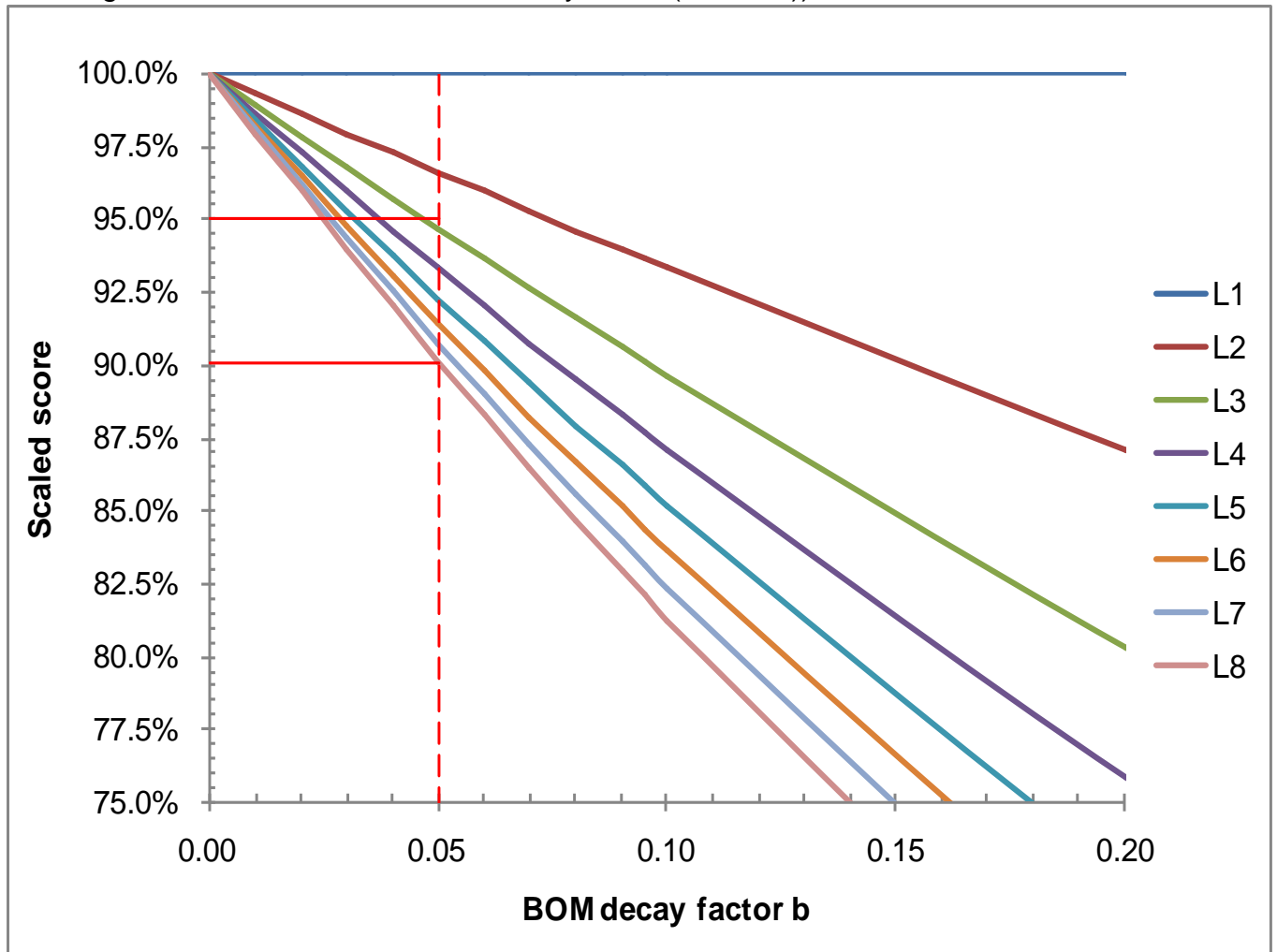


Figure 9 Scaled score vs. BOM decay factor ( $0 < b < 0.2$ ) for BOM levels 1 to 8



As seen in Figure 9 the BOM decay factor of 0.050 indicates that a part at the 3<sup>rd</sup> level will have its score reduced by 5%. A part at the 8<sup>th</sup> level of a BOM will have its score reduced by 10% implying that the part at the 8<sup>th</sup> level of a BOM will be 10% more difficult to manage than a part in the 1st level of BOM. The use of the BOM decay factor of 0.050 is only a proxy at this time. A more thorough estimation of the decay factor and the decay function is needed based on industry analysis.

Similarly the scaling of the supply chain risk score as a function of the complexity factor  $r$  and part numbers is shown in Figure 10 and Figure 11. Once again the

complexity factor  $r$  used in the models is 0.010 and is arbitrarily selected at this time. The complexity factor decreases the score of a BOM level with 100 parts by 5%. The score of a BOM level having 1000 parts is reduced by 7%. This reduction implies that its only 2% more difficult to manage 1000 parts compared to 100 parts. This seems as a very small difference for an order of magnitude increase in part numbers. As with the BOM decay factor further research is needed to better determine the range of the complexity factor.

Figure 10 Scaled score vs. complexity factor ( $0 < r < 1$ ) for different number of parts

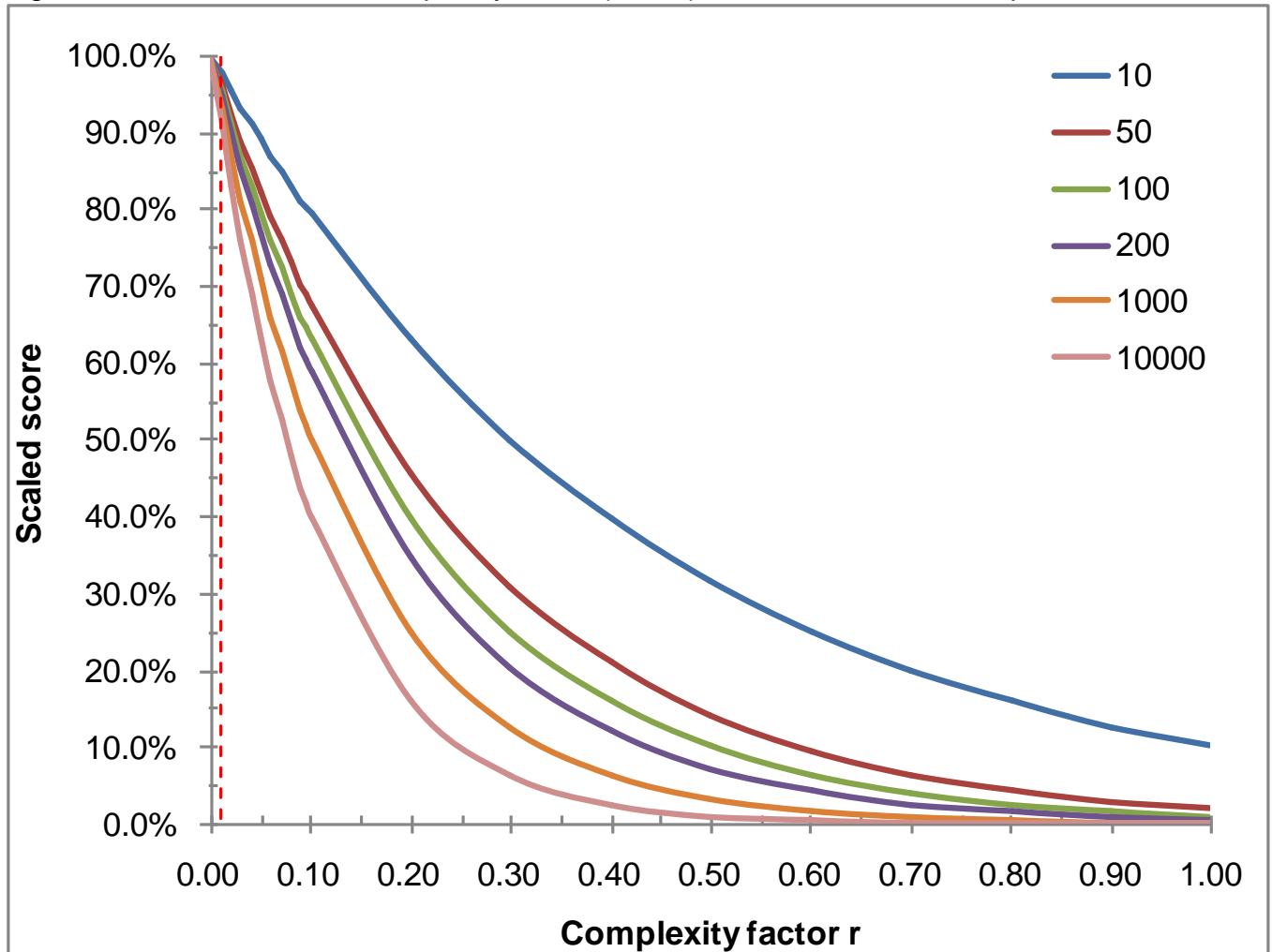
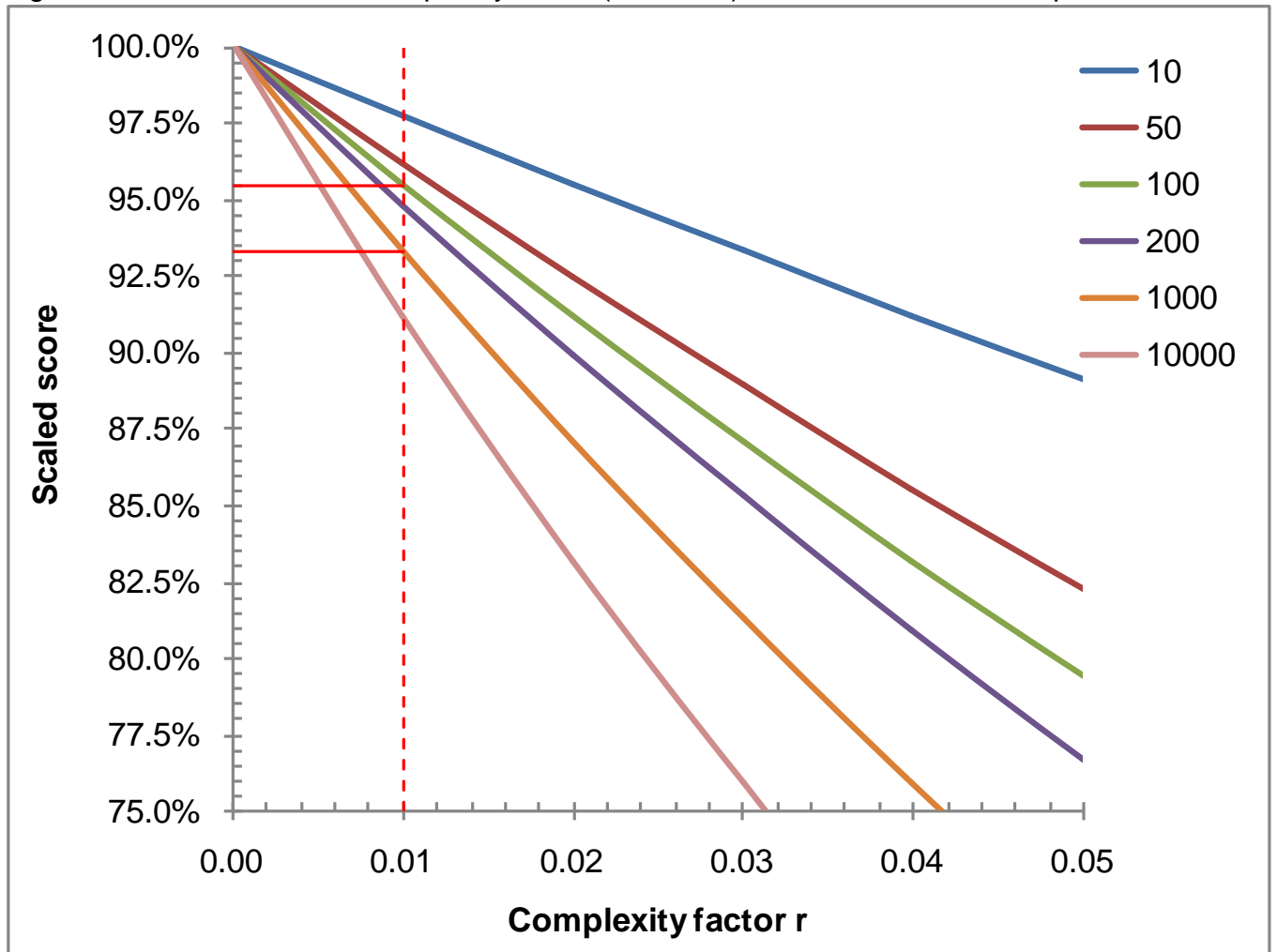


Figure 11 Scaled score vs. complexity factor ( $0 < r < 0.05$ ) for different number of parts



The scaled (S) supply chain risk score,  $SCRS_L^S$  of each level, L, is aggregated to the product level using the harmonic mean as was previously done for the raw product Supply Chain Risk Score:

$$SCRS_P^S = \frac{\lambda}{\sum_{L=1}^{\lambda} \frac{1}{SCRS_L^S}} \quad (5)$$

Where

$SCRS_P^S$ : is the scaled Supply Chain Risk Score for product P

$SCRS_L^R$ : is the scaled Supply Chain Risk Score for each BOM level, L.

$\lambda$ : is the total number of BOM levels.

L: is the BOM level.

It should be noted that for  $r=b=0$  then  $SCRS_L^S = SCRS_L^R$  and  $SCRS_P^S = SCRS_P^R$

The raw and scaled supply chain risk scores for each product are then rolled up to total supply chain metrics for the enterprise, E,  $SCRS_E^S$  and  $SCRS_E^R$ . The roll up is based on scaling each of the two product supply chain risk metrics by the contribution fraction,  $\varphi_P$ , of each product to the profits of the company.

$$SCRS_E^S = \sum_{P=1}^{\varpi} \varphi_P \times SCRS_P^S \quad (6)$$

$$SCRS_E^R = \sum_{P=1}^{\varpi} \varphi_P \times SCRS_P^R \quad (7)$$

Where

$SCRS_E^S$ : Supply Chain Risk Score, subscript E for Enterprise, superscript S for scaled

$SCRS_E^R$ : Supply Chain Risk Score, subscript E for Enterprise, superscript R for raw

$\varphi_P$ : product contribution fraction to enterprise profits, where  $\sum_{P=1}^{\varpi} \varphi_P = 1$

P: products from 1 to  $\varpi$

The example on the following page demonstrates the proposed risk assessment system in a spreadsheet format (Figure 12). The user is further assisted in the management of the supply chain risk by indicators of how many part numbers are ranked at each level (4 to 1) within each BOM level as well as for the product level. An

additional indicator is the percentage of part numbers with a particular score (1-4) as a fraction of the total population of part numbers for each product. Lastly the monetary contribution of each product to the profits of the enterprise is indicated.

Figure 12 Supply Chain Risk Scorecard

Enterprise		Profit (\$)	Complexity decay factor, r								
SC Risk Score (raw)	SC Risk Score (scaled)	\$ 60,000,000	0.010								
4.000	3.848	Profit contrib.	BOM level	1	2	3	4	5	6	7	8
100%	96%		BOM level decay factor, b	100%	97%	95%	93%	92%	91%	91%	90%
				<b>SCRS<sub>L</sub><sup>R</sup></b>							
P r o d u c t  1	3.600	3.461	90%	<b>SCRS<sub>P</sub><sup>R</sup></b>	4.000	4.000	4.000	4.000	<b>SCRS<sub>L</sub><sup>S</sup></b>		
	Profit contrib. (% and \$)	\$ 54,000,000	<b>SCRS<sub>P</sub><sup>S</sup></b>	4.000	3.846	4.000	3.802	3.745			
			Number of 4's	9	100%	1	5	3			
			Number of 3's								
			Number of 2's								
			Number of 1's								
			Total number of parts	9		1	5	3			
				<b>Part no score x<sub>i</sub></b>							
				4	4	4					
				4	4						
				4	4						
				4							
				4							
P r o d u c t  2	0.400	0.387	10%	<b>SCRS<sub>P</sub><sup>R</sup></b>	4.000	4.000	4.000	<b>SCRS<sub>L</sub><sup>S</sup></b>			
			\$ 6,000,000	<b>SCRS<sub>P</sub><sup>S</sup></b>	3.867	4.000	3.822				
			Product level indicators	Number of 4's	5	100%	1	3	1		
				Number of 3's							
				Number of 2's							
				Number of 1's							
				Total number of parts	5		1	3	1		
				<b>Part no score x<sub>i</sub></b>							
				4	4	4					
				4							
				4							

## **4.2 Supply Chain Risk Model discussion**

The model presented thus far is able to determine the supply chain risk score of an enterprise. The discussion that follows presents four scenarios to demonstrate aspects of the model and can provide insights on the risk metric of a supply chain. The models will demonstrate the following scenarios:

Scenario 1: A product with the same number of parts but distributed differently within the BOM.

Scenario 2: The effect of a medium risk part at different BOM levels

Scenario 3: The effect of one medium risk part vs. two low risk parts.

Scenario 4: The effect of one medium risk part or two low risk parts at different BOM levels.

These scenarios are only a sample of the possible circumstances that can be encountered in a supply chain. They are based on some of the circumstances that can face users in the application of the model. The discussion provides some guidance on possible approaches to addressing supply chain risk.

### **4.2.1 Scenario 1: A product with the same number of parts but distributed differently within the BOM.**

In the first scenario two products made of eight part numbers are compared. Product 1 has one part at the BOM level 1, five parts at BOM level 2 and two parts at

BOM level 2. The second product has one part at the BOM level 1, three parts at BOM level 2, three parts at BOM level 2 and 3. All parts are rated with a 4 for no risk. The Supply Chain Risk Score, SCRS, for each product is the same (4) when the effect of product complexity is ignored (thin arrows). However, the scaled SCRS for each product is lower, product 1 has a score of 3.851 and product 2 a score of 3.819. This difference in SCRS is due to the product complexity (number of BOM levels and number of parts). This difference in SCRS of products made of parts with very low risk could drive supply chain managers to try and decrease the complexity of products by either reducing the number of BOM levels in a product or the number of parts. For a product with fixed functionality the reduction in the number of BOM levels could result in more assembly steps being done all at once.

One needs to keep in mind that the underlying assumption of the model is that as production transitions between BOM levels, hand-offs take place between different members of a supply chain. For example, a computer has a BOM that at level 1 would be the Central Processing unit (CPU), usually assembled at an integrator or Electronic Manufacturing Services company. At the second BOM level, the CPU is composed of a chassis, a power supply, a motherboard, a graphics card, a hard drive and an optical drive. These five parts can be sourced from different suppliers and being assembled by the integrator. Similarly, the motherboard, at BOM level 3, is consists of a printed circuit board and components sourced from hundreds of suppliers. At each BOM level there is a change of ownership and transfer of parts that requires increase visibility as well as management of the risk to a disruption.

Scenario 1							
<b>SCRS<sup>R</sup><sub>P</sub></b>	→	<b>4.000</b>		4.000	4.000	4.000	
<b>SCRS<sup>S</sup><sub>P</sub></b>	→	<b>3.851</b>		4.000	3.802	3.760	
Number of 4's		8	100%	1	5	2	
Number of 3's							
Number of 2's							
Number of 1's							
Total number of parts		8		1	5	2	
Product 1				4	4	4	
					4	4	
					4		
					4		
					4		
Scenario 2							
<b>SCRS<sup>R</sup><sub>P</sub></b>	→	<b>4.000</b>		4.000	4.000	4.000	4.000
<b>SCRS<sup>S</sup><sub>P</sub></b>	→	<b>3.819</b>		4.000	3.822	3.760	3.706
Number of 4's		8	100%	1	3	2	2
Number of 3's							
Number of 2's							
Number of 1's							
Total number of parts		8		1	3	2	2
Product 2				4	4	4	4
					4	4	4
					4		

#### 4.2.2 Scenario 2: Effect of a medium risk part at different BOM levels

The second scenario is a comparison of two products with identical BOM structure. Product 1 has one medium risk (2) part at BOM level 3. Product 2 has one medium risk (2) part at BOM level 2. All other parts are no risk (4). The raw SCRS for both products is 3.429. On the other hand, the scaled SCRS for product 1 is 3.298 while for product 2 its 3.308. This difference is due to the effect of the BOM complexity factor,  $r$ , which discounts the risk score of a part located at higher levels of a BOM. Hence it is preferred to have a risky part further up in the supply chain, closer to the

product (level 2 part). The underlying assumption is once again that higher visibility exists in the sourcing organization for parts in proximity to the final product than for distant parts in the supply chain. This should lead to a behavior where riskier parts sourced from higher Tier suppliers are addressed first. However this behavior is only observed for the scaled supply chain risk scores. As noted the raw SCRS does not show a preference as to where a riskier part is located in the BOM. If the decay functions and constants are not the same across industries and companies than only raw scores can be compared between companies and products.

Scenario 2

<b>SCRS<sup>R</sup><sub>P</sub></b>	<b>3.429</b>		4.000	4.000	2.667	
<b>SCRS<sup>S</sup><sub>P</sub></b>	<b>3.298</b>		4.000	3.837	2.507	
Number of 4's	4	80%	1	2	1	
Number of 3's						
Number of 2's	1	20%			1	
Number of 1's						
Total number of parts	5		1	2	2	
<b>Product 1</b>			4	4	2	
				4	4	
<b>SCRS<sup>R</sup><sub>P</sub></b>			<b>3.429</b>	4.000	2.667	4.000
<b>SCRS<sup>S</sup><sub>P</sub></b>			<b>3.308</b>	4.000	2.558	3.760
Number of 4's	4	80%	1	1	2	
Number of 3's						
Number of 2's	1	20%		1		
Number of 1's						
Total number of parts	5		1	2	2	
<b>Product 2</b>			4	2	4	
				4	4	

A high risk part at level 2 preferred to one at level 3

### 4.2.3 Scenario 3: The effect of one medium risk part vs. two low risk parts.

The third scenario demonstrates the effect of having a medium risk part in the BOM. Product 1 has two low risk parts with a rating of 3 at BOM level 2. Product 2, on the other hand, has one medium risk part with a rating of 2 and a no risk part with a rating of 4 at BOM level 2. The raw SCRS is 3.000 in the product 1 compared to 2.667 for product 2. Similarly the scaled SCRS is 3.474 and 3.308. This scenario indicates that management should try to first improve part numbers that have a medium or high risk score before addressing parts with low risk. This recommendation is independent of the use of the scaled or raw SCR scores. The additional indicators, such as the number of parts with each ranking, can help identify higher risk parts within a product quickly in order to be addressed to reduce supply chain risk.

Scenario 3

<b>SCRS<sup>R</sup><sub>P</sub></b>	<b>3.600</b>		4.000	3.000	4.000
<b>SCRS<sup>S</sup><sub>P</sub></b>	<b>3.474</b>		4.000	2.878	3.760
Number of 4's	3	60%	1		2
Number of 3's	2	40%		2	
Number of 2's					
Number of 1's					
Total number of parts	5		1	2	2
<b>Product 1</b>			4	3	4
				3	4
<b>SCRS<sup>R</sup><sub>P</sub></b>	<b>3.429</b>		4.000	2.667	4.000
<b>SCRS<sup>S</sup><sub>P</sub></b>	<b>3.308</b>		4.000	2.558	3.760
Number of 4's	4	80%	1	1	2
Number of 3's					
Number of 2's	1	20%		1	
Number of 1's					
Total number of parts	5		1	2	2
<b>Product 2</b>			4	2	4
				4	4

One high risk (2) part is worse than two low risk

#### **4.2.4 Scenario 4: The effect of one medium risk part or two low risk parts at different BOM levels**

The fourth scenario is a variation of the third where product 1 has a medium high risk (2) part at level 2 and product 2 has two low risk (3) parts at BOM level 3. The scenario is looking at the preferred location of a high risk part within a BOM. As seen the raw product SCRS is the same for both products at 3.600. This would imply that the risk for these two products is equivalent. This is a shortcoming of the current model it cannot differentiate between the two cases. The scaled SCRS for product 1 is 3.469 and for product 2 it is 3.463. The model places a higher premium to parts with risk at higher BOM levels. Furthermore, the additional indicators on the percentage of part numbers in each risk category should lead management to address the parts with lower risk scores as product 1 has 17% of parts with a score of 2 while product 2 has 0% parts with a score of 1 or 2. As earlier stated, attention should be focused first on addressing parts with the lowest risk scores, 1 then 2 before moving up to the less risky parts with a score of 3.

### Scenario 3

<b>SCRS<sup>R</sup><sub>P</sub></b>	<b>3.600</b>		4.000	3.000	4.000
<b>SCRS<sup>S</sup><sub>P</sub></b>	<b>3.469</b>		4.000	2.866	3.760
Number of 4's	5	83%	1	2	2
Number of 3's					
Number of 2's	1	17%		1	
Number of 1's					
Total number of parts	6		1	3	2
			4	2	4
				4	4
				4	
<b>SCRS<sup>R</sup><sub>P</sub></b>	<b>3.600</b>		4.000	4.000	3.000
<b>SCRS<sup>S</sup><sub>P</sub></b>	<b>3.463</b>		4.000	3.822	2.820
Number of 4's	4	67%	1	3	
Number of 3's	2	33%			2
Number of 2's					
Number of 1's					
Total number of parts	6		1	3	2
			4	4	3
				4	3
				4	

### 4.3 Guidelines for users

The prioritization should be linked in the mind of the user to the score ranking and the scale used. A part with a score of 1 is most critical as the Business Recovery Time (BRT) is unknown and no plan exists addressing the recovery process. Similarly, a part with a score of 2 does have a recovery plan but a BRT exceeding the inventory days of supply at the next level. The result from a disruption of a part with a score of 2 will, most likely, be that supplies will be exhausted and the flow of goods will be disrupted.

The model provides the user with the monetary profit contribution to the enterprise for each product. The intention for this metric is to be used as a comparison to improvement plans. The cost of any plan to raise a part number's score needs to be compared to the profit contribution. An improvement plan for a part number that exceeds the profit contribution of a particular product should be scrutinized. For example if the improvement to raise a part from a score of 1 to 2 costs \$1M but the profit contribution of the product is only \$200K the improvement may not be justifiable.

Other aspects that need to be considered besides the profit contribution are the strategic intentions of the company and the lifecycle of the product. In the above case if the product is during its launch phase and profits are expected to improve in subsequent years the improvement effort may be worthwhile. Similarly, if the product is targeted into a particular market segment that the company is trying to enter than the investment may be worthwhile. Conversely, if the company is exiting the particular market segment or the product is close to the end-of-life than any further investment may not be justified.

In my discussions with supply base professionals from HighTech the model was seen as innovative. The approach does not bring in the complexities of probabilities for different events, which are difficult for a company to assess. The implementation of the system in a corporate setting was raised as a concern. The model requires that all part numbers be ranked based on the scale of low risk (4) to high risk (1) (Table 3). This can be a long process when more than a few hundred part numbers are used throughout the products of a company. In the case of HighTech this effort would be similar in scale to the effort for updating all part numbers with Restriction of Hazardous

Substances Directive (ROHS) status information. However, guidelines could further assist in automating the risk assessment process. As an example, parts that are sourced from more than three suppliers and are commoditized could be ranked with a low risk of 4. Parts that are single sourced would need to be analyzed with a higher scrutiny before determining their supply chain risk score.

Up to this point the model for assessing the supply chain risk has been presented. The next step would be to look at how to improve the score rating. The score of each part number, and by extension the product score and the enterprise score, can be improved by two approaches. One approach to improve the score of a part is to put in place inventory to exceed the business recovery time from a disruption. This approach will result in increased inventory within the supply chain. The large inventories can have detrimental effects in the supply chain as more inventories can lead to larger inventory carrying costs and larger charges for excess and obsolescence of material.

The second approach to improve the score of a particular part number is to develop an efficient recovery plan that reduces the business recovery time (BRT) well below the days of supply of the part at the next level within the supply chain. One approach is to have multiple active sources of the part or qualified suppliers that can quickly provide supply. One concern to have in such cases is that a disruption that impacts a particular part with multiple consumers will force the customer to turn to the same alternate suppliers. In such a case, the allocation of the production at the alternate supplier can become a contest between customers.

The supply chain risk metric model provides one metric for evaluating a supply chain for risk. However, a supply chain needs to be evaluated using a variety of supply chain metrics to look at different factors. Such metrics include but are not limited to those recommended by the SCOR model, for example: Perfect Order Fulfillment, Order Fulfillment Cycle Time, Cash-to-Cash Cycle Time (Supply Chain Council, 2005).

The supply chain risk metric developed through this model provides an insight into the ability of a supply chain to recover from a catastrophic disruption impacting a part in a Bill-of-Material (BOM). It accounts for the difficulties of managing products with increasing complexity due to the number of parts and depth of the BOM. The model creates a metric that could be used to compare supply chain risk across companies and industries for BOM based product. The model could be extended to other industries, where a BOM is not present but other hand-offs in information, currency and product take place.

# 5 Conclusions

This research identified two of the factors that have enabled the rapid recovery from a supply chain disruption using cases from a single company in the information technology sector. In the two cases documented two main factors were identified. One factor was effective and rapid communication between stakeholders across the supply chain. The use of cross-functional teams and meetings kept stakeholders involved and informed of the recovery process. The close relation and monitoring of upper tier suppliers (2<sup>nd</sup>, 3<sup>rd</sup> etc) enable better visibility in the supply chain before a disruption occurs. The close communication and monitoring of all members of a supply chain permits early detection and reaction to a disruption. The early detection can minimize the impact of the disruption and provide valuable time to start recovery efforts.

The second factor that enabled a successful recovery was presence of sufficient inventory downstream of the disruption not to stop the continuity of supply. Although the overabundance of inventory is viewed as negative, inventory extends the timeframe during which recovery from a supply chain disruption can take place.

The observed relation between inventory and ability to recover, from a supply chain disruption, led to the formulation of the supply chain risk score model. The model is based on principals used at Ericsson (Norrman & Jansson, 2004). However this model is simplified by disregarding the probabilities of different disruption events taking

place. The model is focused on the aftermath from a disruption event and in particular the recovery and return to normalcy. The model assists users in focusing attention to the high risk parts. In general, parts with high and medium risk should be addressed first. The risk can be reduced by effecting either reducing the business recovery time (BRT) or increasing the inventory of finished parts. The BRT can be reduced by qualifying alternate suppliers or increasing available capacity with multiple current suppliers. In all cases a recovery plan for each part should be developed before a disruption occurs. The cost of the risk reduction effort through BRT or inventory should be compared to the profit contribution of the product. If the cost exceeds the profit contribution than the reduction in risk may not be justifiable.

The model was developed based on a company with a product structure based on the use of bill of materials (BOM). The next step would likely be to apply the model to an actual case and better understand its strengths and weaknesses. HighTech has expressed interest in using this model to assess its supply chain risk at this time. The use of the model is easy to teach to potential users thus making it attractive for implementation.

The model should be extended for use in other industries such as pharmaceuticals, fresh produce and service industries. As an example, for bananas, the different BOM levels may be interpreted as the different changes in ownership/hand off of product from the producer, to the wholeseller, to the brand and finally to the supermarket and the customer. Similarly, service industries such as cruise operators may consider their supply chain risk in the operation of a cruise, from the flow of supplies and the flow of vacationers to its cruise vessels. Once again the BOM levels

may be considered as the steps within the supply chain where the product changes ownership.

In conclusion, this study identified two factors contributing to successful recovery from supply chain disruptions: open and efficient communications across the supply chain and inventory position downstream from the disruption. The latter factor spurred the development of a model for assessing supply chain risk of products using a bill-of-material. The model considers the complexity of the product and the ability for each part number to be sourced following a disruption within a timeframe relative to the days of supply downstream from the disruption.

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