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RISK MANAGEMENT OF COMPLEX SUPPLY CHAINS PART 1: SUPPLY CHAIN RISK AND COMPLEX SYSTEMS

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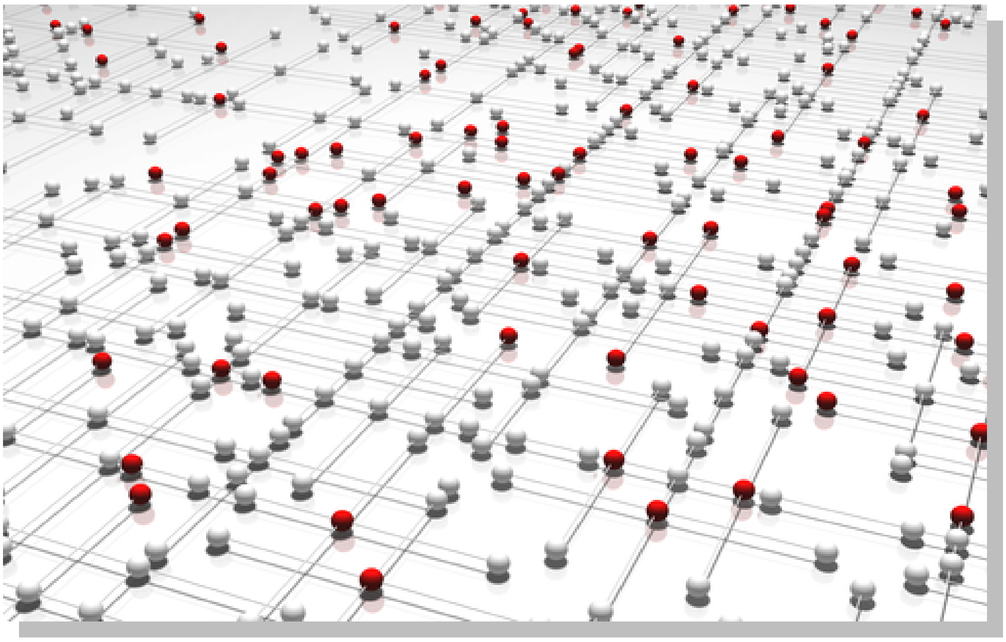

A Collaboration Between

Institute of High Performance Computing (A*STAR)

Singapore Institute of Manufacturing Technology (A*STAR)

The Logistics Institute Asia Pacific

RISK MANAGEMENT OF COMPLEX SUPPLY CHAINS PART 1:

SUPPLY CHAIN RISK AND COMPLEX SYSTEMS

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EXECUTIVE SUMMARY

Supply chains in the current age are complex networks as the result of globalization, outsourcing, and lean initiatives. Globalization increases the complexity of the traditional supply chain yielding more nodes, longer links, greater connection among the links, and more collaboration among the nodes. Outsourcing provides the benefit of economies of scale but at the same time weakens the direct relationship between buyers and suppliers or shippers and carriers. Lean initiatives such as just-in-time practice promote supply chain efficiency as they get rid of inventory buffers, which are critical to help a supply chain to sustain and recover when facing disruption risks.

In this complex environment, we hypothesize that the efforts from a single company in the context of a network is far from enough to cover it from many risks, especially those passed down from other companies, or those from risk reactions of a competitor company. The traditional mitigation approaches are limited in those areas. Risk management of complex supply chain networks is thus important and urgently needed, especially when the past decade has witnessed an ever-increasing number of disasters and disruptions to business.

A framework of supply chain risks should be developed to cover all possible types of risks to help companies systematically identify the potential risks. Under an environment of imbedded risks, the network of supply chains should be studied to understand the propagation of such risks. Finally, the technologies to manage supply chain risks should be reviewed in order to determine the state of progress. The three topics are addressed in a series of three white papers conducted by a research consortium of TLIAP, IHPC and SIMTech, which is supported by A*Star to study the implication of risks for a complex supply chain network.

This set of white papers is the first installment of a series addressing the framework of supply chain risks and complex system. The framework is developed to facilitate the identification of risks that require interaction among the supply chain entities. Those interactions have to be put in a context of a complex system in order to find proper interaction rules to predict system behavior.

1. INTRODUCTION

The supply chain network is a complex network of business entities involving the upstream and downstream flows of products and/or services, along with the related financial flows and information. It becomes more complex due to the adoption of contemporary practices such as lean initiatives, just-in-time sourcing, globalization, outsourcing, multi-tiered partners, coordination, and sustainability. The benefits to these new practices are significant but the increased supply chain complexity, emphasis on efficiency, extended coordination with external stakeholders also suffer from vulnerability, especially, when disasters or economic crises seem to occur with a greater frequency recently.

The first step in supply chain risk management is to identify the risks. Companies need to scrutinize their supply chains in a systematic way to find the potential risks they are exposed to. Then those risks should be analyzed to ascertain their severity, probability of occurrence, triggering conditions, propagation patterns, and so on. Third, the pre-risk preparation can be realized through building early warning systems, establishing resilience and responsiveness, as well as business continuity plans. Fourth, proper mitigation actions are executed when risk occurs. Finally, monitoring systems should be active to sense the emergence of risks.

The aims of the current white paper are as follows:

a. To develop a supply chain risk framework to help companies to systematically identify the potential risks. The framework can further help to identify the risks related to the mitigation interactions among the supply chain entities. The results of those interactions may not be within the expectation of a single entity but have to be understood only treating a supply chain as a complex system.

b. Treat the supply chain network as a complex system and use the principles of complexity to manage supply chain risk.

c. Take the risk of disruption as an example to demonstrate the risk propagation/cascading and identify the interactions that have to be considered in a complex system to determine efficient mitigation solutions.

2. SUPPLY CHAIN RISKS

As mentioned, today's supply chain is always complex and their risks are generally identified according to the origins and mitigation strategies are then developed targeting on those particular risks. However, further risks can be generated from the reactions of a supply chain entity. Thus, a framework which can help identify this type of risk should be proposed. In Figure 1, supply chain risks are categorized at three levels according to their scopes: supply chain, cross supply chain/industry, and macro level.

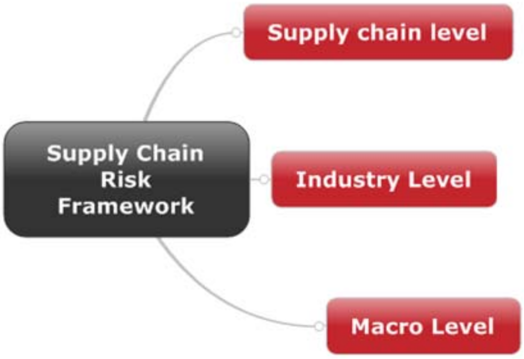

Figure 1: Supply chain risk framework

2.1 RISKS AT SUPPLY CHAIN LEVEL

2.1.1 Types of Risk

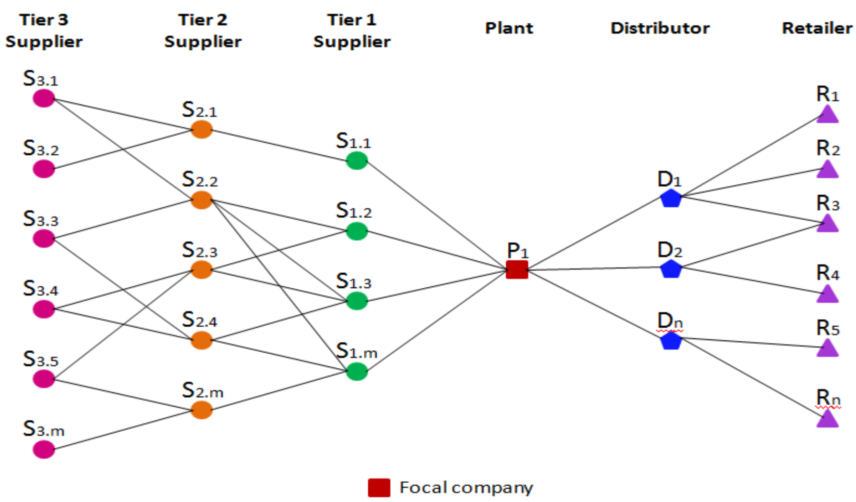

Figure 2: Generic supply chain networks with one focal company

The risks in a supply chain level refer to the risks occurring in the supply chain of a focal company. All risks are identified from this company's point of view. For example, Figure 2 shows the generic supply chain networks with one focal company P_1, which has three tiers of suppliers, one tier of distributors, and one tier of retailers. The possible risks of P_1 can be further decomposed into three categories: sourcing side, internal process, and demand side risks (Figure 3).

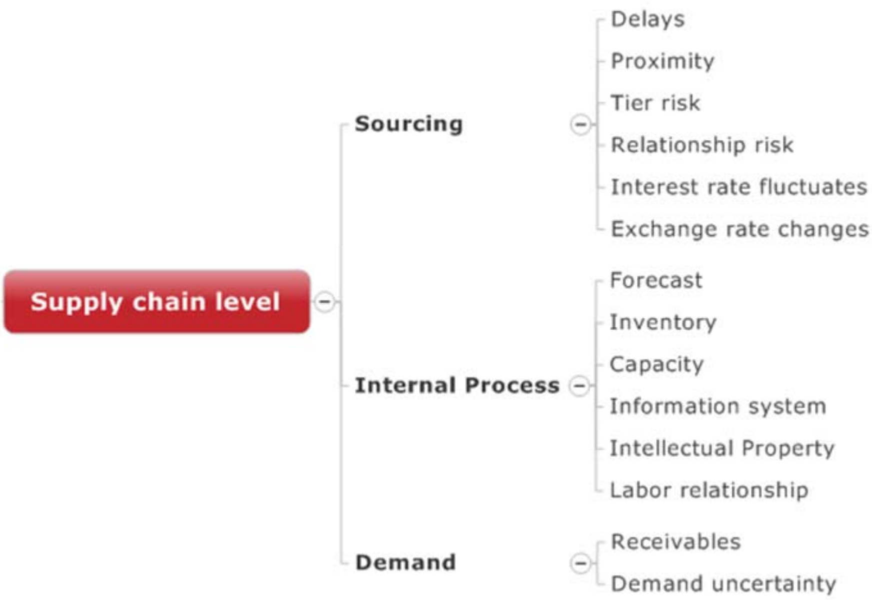

Figure 3: Types of risks at the supply chain level

On the sourcing side, the focal company can face risks such as delivery delays, proximity risk, tier risk, performance risks, interest rate fluctuations, exchange rate changes, and so on. We clarify some of these notes below.

- Delay in material flows is normally the result of the inability of a supplier to respond to changes in downstream demand. But it could also be caused by the unsatisfactory quality of supply or the delay in transportation.
- Proximity risk refers to the risk from the geographic distance of a focal company's suppliers, which may be located within the same disaster zone. In the case of a disaster, those suppliers may fail to provide materials at the same time and thus causing supply shortage to the focal company.
- Tier risk refers to the risk brought out not by the focal company's first tier partners (e.g. $S_{1.1}$, $S_{1.2}$) but by its tier 2 or higher level partners (e.g. $S_{2.1}$, $S_{3.1}$) due to single sourcing or proximity risks. For example, the Japan Triple Disaster in 2011 put Apple at risk through its

tier 4 supplier, ELectrotechno (Mitsubishi Gas Chemical Sub), which provided BT resin to Apple's tier 3 suppliers but was hit by the disaster at Fukushima. At the time just before the disaster, ELectrotechno in Fukushima produced about 50% of global BT resin supply.

- Relationship risk is explained in section 4.3.
- Interest rate fluctuations and exchange rate changes refer to how changes in the rate can affect business operations. This was particularly relevant during the recent global financial crisis, when the U.S. dollar devalued sharply, also affecting the exchange rate of other countries' currencies.

In the internal processes, risks can be in the form of forecast inaccuracy, inventory, capacity, information system, intellectual property, labor-employer relationship, etc.

- Forecast risk, such as the bullwhip effect, results from a mismatch between a company's projections and actual demand. Inaccurate forecasts may occur due to long lead times, seasonality, product variety, short life cycles, and small customer base. Bullwhip effect or information distortion due to sales promotions, incentives, lack of supply-chain visibility and exaggeration of demand in times of product shortages also constitute forecast risks.
- Inventory risks can be driven by the rate of product obsolescence, inventory holding cost, product value, demand and supply uncertainty, etc.
- Capacity risks can be caused by capacity's cost and inflexibility.
- Information system risk can be driven by the information infrastructure breakdown or improper integration among the internal or external systems. The failure of an information system can have severe consequences like interrupted production and delayed order fulfillment. Information system is especially important for an E-commerce company.
- Intellectual property breach can be from the vertical integration of the supply chain or global outsourcing and market (Chopra and Sodhi, 2004).
- Labor relationship risk in the form of labor disputes or strikes can bring a company great losses such as low productivity.

On the demand side, a focal company typically encounters risks of receivables and demand uncertainty.

- Receivable risk is related to number of customers and their financial strength.
- Demand uncertainty can be caused by life cycles of high-technology products, or higher levels of competitive activity, such as sales incentives and promotions. These sorts of risks can occur due to shortage of materials, loss of access to supplier, an inaccurate prediction of demand, and logistics or information technology failures.

2.1.2 Mitigation Approaches

From the works of Chopra and Sodhi (2004), Sheffi (2005), and Tang (2006), the following mitigation methods for the risks in the supply chain level are summarized. It should be noted that all the methods need the action of the focal company or the interaction between the focal company and an entity in the same supply chain.

- Increase capacity
- Redundant suppliers
- Increase responsiveness
- Increase inventory
- Increase flexibility
    - Flexibility through interchangeability achieved by standard facilities, parts, and processes.
    - Flexibility through postponement
    - Flexibility through supply
    - Flexibility through distribution
- Demand shaping
    - Pooling or aggregation
    - Dynamic pricing and promotion
    - Shifting demand across time (for uncertain demand)
    - Shifting demand across markets
    - Product substitution
    - Product bundling
- Increase capability

2.2 RISKS AT THE INDUSTRY LEVEL

Risks at an industry level refer to the risks occurring in the common resources shared by supply chains of different focal companies in the same industry. For example, Figure 4 shows that two competitive companies share some common resources in their supply chains, e.g. $S_{1.2}$, $S_{1.3}$, $S_{1.m}$, D_1, and D_2. For each company, it not only has its own supply chain level risks described in the previous section, but also industry level risks categorized in Figure 5, e.g. sourcing, demand pattern, trading pattern, technology change, and political/regulation changes.

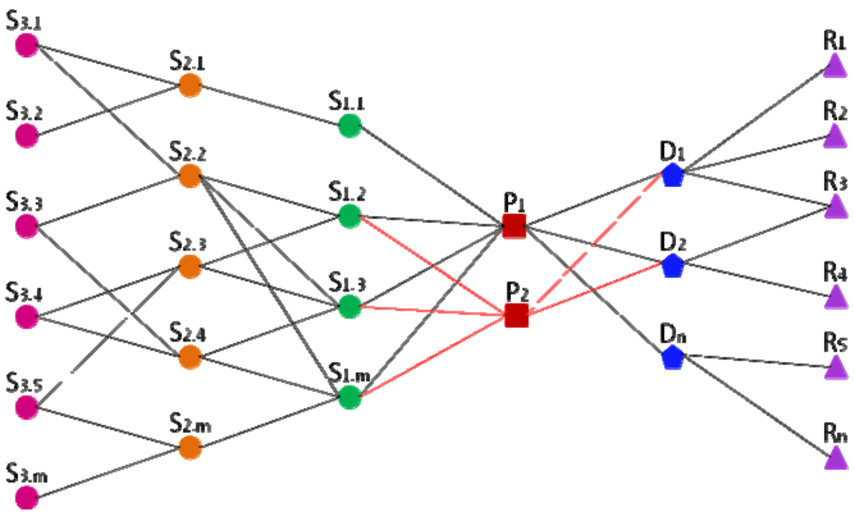

Figure 4: Supply chains with two focal companies

Figure 5: Risks at the industry level

On the sourcing side, we identify two risks such that the impact of them on a focal company may be affected by the reaction of the focal company's competitor. Those two risks are competitive risk and cluster risk.

2.2.1 Competitive Risk

In Figure 6, both plants P_1 and P_2 source materials from the same supplier $S_{1.1}$. After a disruption, supplier $S_{1.1}$ is no longer able to provide supply to plants P_1 and P_2. As the result, two plants have to turn to an alternative supplier, say, supplier $S_{1.2}$.

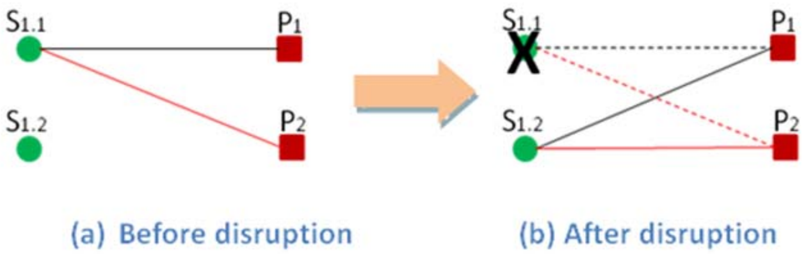

Figure 6: Competitive risk

At this time, there will be no question if supply $S_{1.2}$ has enough capability to meet both P_1 and P_2's demands. However, if $S_{1.2}$ has only limited capacity, according to Hopp *et al*. (2008), the following factors may influence supplier $S_{1.2}$'s decision of to whom it is going to provide supply.

- Plant size
- Willingness to pay
- Plant preparedness
- Business history
- Contractual agreements
- First-come-first-served
- Market share of P_1 and P_2

On the other hand, when a plant can secure supply from supplier $S_{1.2}$, it still needs to decide the amount of supply according to its competitive strategy. An extreme example could be that the plant sweeps all the supply that supplier $S_{1.2}$ can provide in order to starve its competitor. In doing so, the plant has to pay the "holding cost" incurred by unnecessary part of supply.

This is exactly what Nokia did when its supplier, a Philips semiconductor plant in Albuquerque, New Mexico, was hit by a lightning bolt in March 2000. The lightning created a 10-minute blaze that contaminated millions of chips and subsequently delayed deliveries to its two largest customers — Finland's Nokia and Sweden's Ericsson. Nokia reacted promptly and swept all available supply from other suppliers. The net result was that Ericsson reported a $400 million loss because it did not receive chip deliveries from the Philips plant in a timely manner and couldn't find alternative suppliers, which had been snapped away by Nokia (Sheffi and Rice, 2005).

Thus, a competitive risk is triggered by the failure of supplier $S_{1.1}$ to focal companies P_1 and P_2. The risk is industry-wised as involved entities like companies P_1, P_2 and supplier $S_{1.2}$ may not be in the same supply chain. The impact of competitive risk to companies P_1 and P_2 is decided by 1) the relative competitiveness of P_1 and P_2 in the view of supplier $S_{1.2}$, 2) the relative promptness of P_1 and P_2 reacting to the risk, and 3) the purchasing plan of P_1 (or P_2) to secure supply from $S_{1.2}$ basing on its own capability and its understanding of P_2 (or P_1).

2.2.2 Cluster Substitution Risk

A cluster is a geographical concentration of organizations in certain interconnected industrial groups tied by competitive pressures to form collaborative and competitive relationship. The California wine cluster, Italian leather goods cluster, fashion cluster in France, Silicon Valley in USA, software outsourcing in India, automotive cluster in Thailand and logistics clusters in Germany, Netherlands and Singapore are a few examples of clusters around the world. Although a cluster has its own advantages like inclusion, collaboration, cooperation for its participants, it is also subject to risks such as natural disasters or substitution by other clusters.

Figure 7 illustrates the risk of cluster substitution. Suppose suppliers $S_{1.2}$, $S_{1.3}$, and $S_{1.m}$ are located in the same industrial cluster, which happens to be in a disaster zone. When a disaster occurs, it is most likely that all three suppliers will be affected, subsequently, bringing the competitive risk to plants P_1 and P_2. The unreliability of those suppliers will naturally urge plants P_1 and P_2 to explore alternative suppliers in other safer areas, e.g. area around suppler $S_{1.1}$. The new suppliers may finally replace the existing ones and trigger the cluster substitution risk to suppliers like $S_{1.2}$, $S_{1.3}$, and $S_{1.m}$.

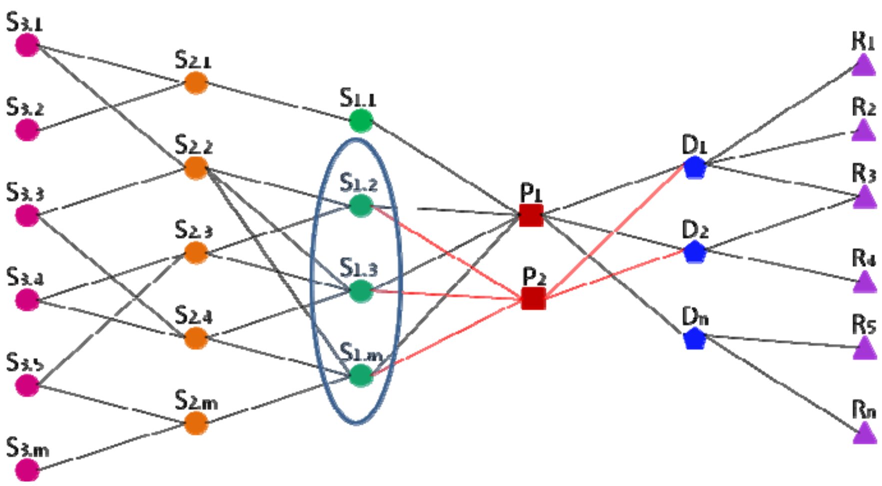

Figure 7: Cluster substitution

The severe Bangkok flood in October 2011 exposed the hard disc drive (HDD) cluster to the significant risk of substitution. The worst flooding in 50 years left production facilities of Western Digital, Hitachi Global Storage Technologies, Seagate, and suppliers of HDD manufacturers like Nidec submerged under water. The damaged production and inventory led to a global HDD shortage and consequently a hike in prices. Once manufacturers or suppliers in the disaster-pro cluster can find safer alternative locations with similar operational environments, the potential risk of cluster substitution may become a reality.

2.3 RISKS AT THE MACRO LEVEL

Risks at the macro level refer to the risks which can impact across the supply chains of different industries. The impacts of a macro risk can be passed from the supply chain of one industry to the supply chain of another industry, and subsequently passed on to other supply chains. Even though the focal company may not be directly hit by the risk, it still can feel risks propagated from the source or from the risk reactions from other entities within or outside its own supply chain.

This type of risks includes natural disasters (e.g. earthquake, tsunami, flood, volcano, and fire), economic instability (e.g. GDP swings and economic crisis or recession), terrorist attacks, social condition, or contagious diseases (Figure 8).

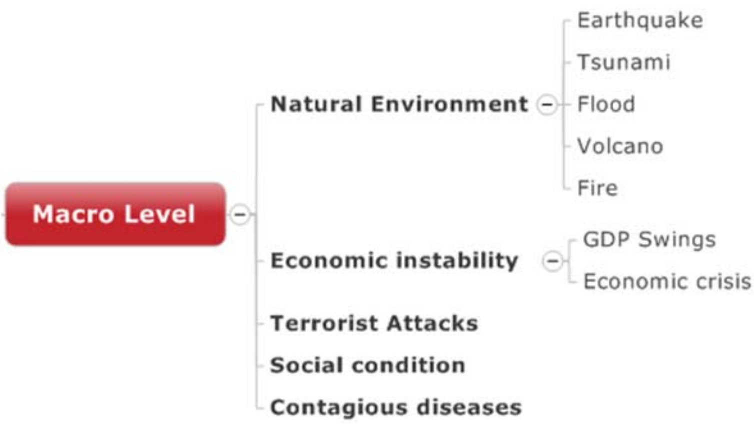

Figure 8: Macro level risks

For example, the triple (9.0 magnitude earthquake, tsunami, and nuclear power plant leak) disasters of Japan in 2011 hit areas of Miyagi, Fukushima and Iwate, which are estimated to contain over 86,000 of the businesses that were affected, as well as US$209 billion in sales volume and 715 industries [1]. Japan is an important part of the chain in global supply networks, particularly the electronics, cars and airplanes, energy and fuel, as well as logistics. But the triple disaster had primary impacts on local operations damaged, personnel lost, communications lost and secondary impacts on downstream customers suffered loss of supply from primary impacts causing shutdowns[2].

By observation, macro level risks have some or all of the following characteristics.

- Across industries
- Across supply chains
- Risk propagation/cascading

2.4 SUPPLY CHAIN RISK FRAMEWORK

The framework of supply chain risks is given in Figure 9, where risks are categorized by three levels according to the different scopes of risk impacts: supply chain, industry, and macro levels.

At the supply chain level, the risks in one supply chain are the focus and the mitigation of them requires the reactions of the risk-hit entity only or interactions of entities from the same supply chain. From the focal company’s point of view, risks are originated from sourcing, demands, and internal processes. In the industrial level, the occurrence of risks will impact entities in different supply chains. The mitigation of them may involve interactions between different entities in different supply chains. Two important risks are identified: competitive risk and cluster substitution risk. At the macro level, the occurrence of risk has a wider impact than the previous two types of risks can do. Risks in this level impact entities across supply chain and industries and they can also propagate from one location to the other.

One important benefit of the framework is to help to identify risks, which are generally ignored in most supply chain risk frameworks. The mitigation of those risks, e.g. relationship

[1] Dun & Bradstreet. (2011). “2011 Impact Report of Japan Earthquake and Tsunami: Preliminary Business Impact Analysis for High Impact Areas of Japan.” *Dun & Bradstreet Website:* http://www.dnbgov.com/pdf/Japan_Earthquake_and_Tsunami_Impact_Report.pdf (accessed on Oct. 16 2012)

[2] J. B. Rice, Jr. (2011). "The Japan Disaster: What Lessons Learned for the Supply Chain?". from http://www.cts.cv.ic.ac.uk/documents/seminars/cts_seminar270.pdf (accessed on Oct. 16 2012).

risk, competitive risk, cluster substitution risk, is not one-man-show but needs interactions from different entities.

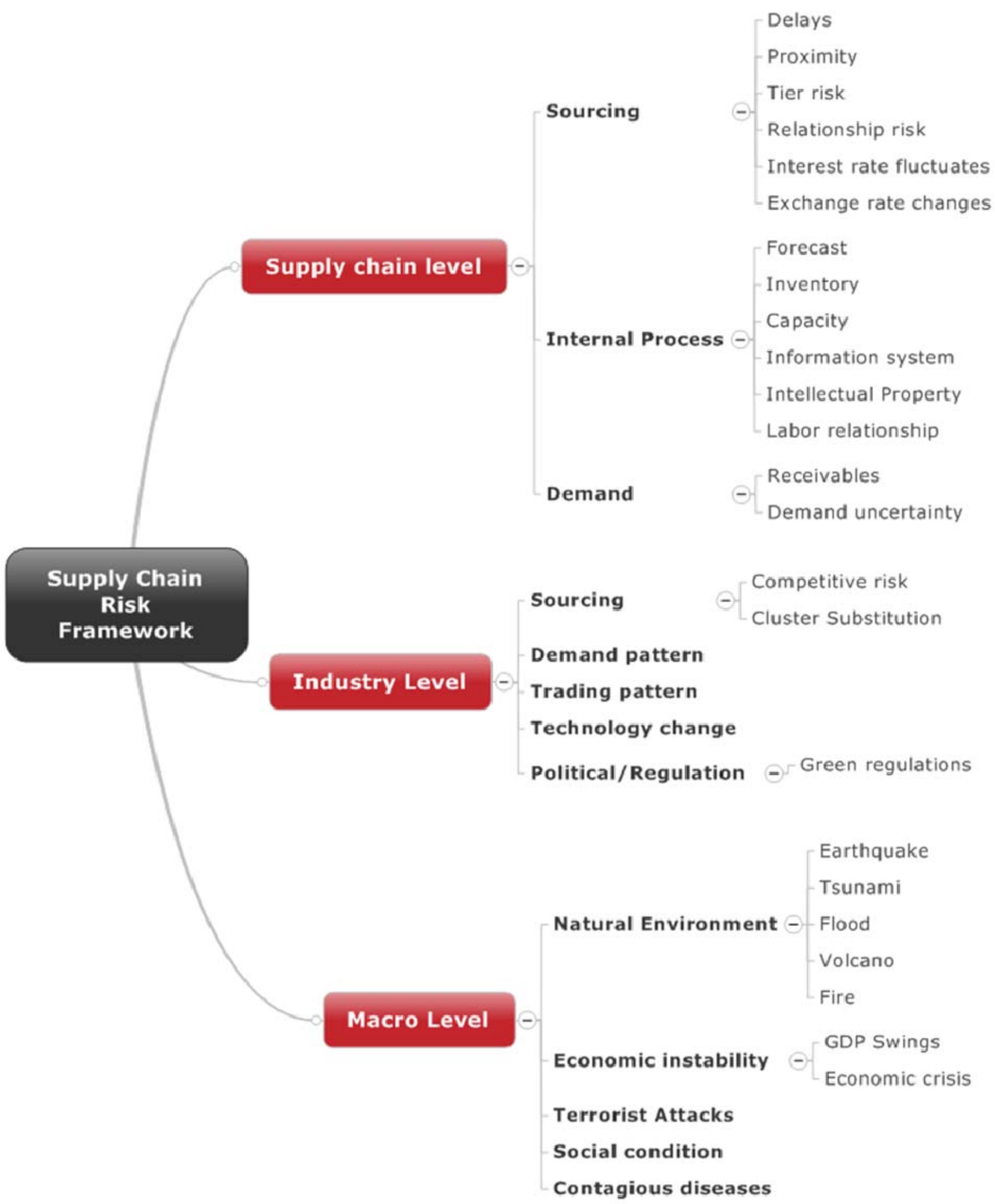

Figure 9: Supply chain risk framework

Data were obtained primarily through interviews with key executives working in the automotive and aircraft industries. Interviews were conducted for 3 automotive companies, 2 aircraft companies and 1 logistics provider over a period of 2 months involving three researchers from TLI – Asia Pacific and two researchers from NTU Center for SCM.

The objectives of this research were:

a) To understand the various service parts logistics practices in automotive and aircraft industries in the Asia-Pacific region.

b) To understand the process flow for service parts logistics in the two industries.

c) To identify trends and opportunities for service parts logistics business in Singapore.

3. COMPLEX SYSTEMS AND SUPPLY CHAIN NETWORKS

Complex systems are the new approach to science that studies how relationships between parts give rise to the collective behavior of a system and how the system interacts and forms relationships with its environment. Simon (1962) described complex systems as consisting of a large number of parts that interact in non-simple ways. The nature of the interaction between two parts may be positive (increasing in one another), negative (decreasing in one another), or unrelated. As a result, overall system performance can exhibit highly nonlinear behavior in response to changes in one or more parts.

The topics in complex systems include emergence, self-organization, collective behavior, networks, evolution & adaptation, pattern formation, systems theory, nonlinear dynamics, game theory, etc. How to describe the important characteristics of certain complex systems, model them, and use the models to try to predict unanticipated behavior are also important topics promising for practical applications.

3.1 A SUPPLY CHAIN NETWORK IS A COMPLEX SYSTEM

Choi *et al*. (2001) recognize a supply network as a complex adaptive system (CAS), which refers to a system that emerges over time into a coherent form, and adapts and organizes itself without any singular entity deliberately managing or controlling it (Holland, 1995). A complex adaptive supply network (CASN) is a collection of firms that seek to maximize their individual profit and livelihood by the exchanging information, products, and services with one another. Therefore, the nature of interactions among firms adjacent in a supply network determines the type of behavior the network as a whole exhibits and the level of control that any one firm has over another (Choi et al., 2001).

3.2 COMPLEXITY OF SUPPLY CHAIN/NETWORK

Network complexity is defined as “the number of dependency relations within a network” (Frenken, 2000) (Greening and Rutherford, 2011) and thus would depend on both the number of nodes in the network and the degree to which they are interlinked. In the context of a supply network, complexity relates to the collective operational burden borne by the members in the network (Choi and Krause, 2006) and in is two forms: static and dynamic (Serdar-Asan, 2011).

- Static complexity is related to the connectivity and structure of the subsystems involved in the supply chain (e.g. companies, business functions and processes); static (structural) complexity describes the structure of the SC, the variety of its components and the strengths of the interactions.
- Dynamic complexity that results from the operational behavior of the system and its environment; represents the uncertainty in the supply chain and involves the aspects of time and randomness

Complexity allows us to understand how supply chains/networks co-evolve as living systems, and it can help us to identify the patterns found in such evolution (Choi *et al.*, 2001).

Supply chain complexity drivers are as follows.

- Number/variety of suppliers
- Number/variety of customers
- Number/variety of interactions
- Conflicting policies
- Demand amplification
- Differing/ conflicting/ non-synchronized decisions and actions
- Incompatible IT systems

Decisions targeting any of the drivers may have an effect on another driver which would then shift the complexity of the supply chain from one driver to another, preferably on which they have greater control. The companies make use of this property when managing the complexity in their supply chains (Li *et al.*, 2010).

4. HANDLING DISRUPTIONS IN A COMPLEX SYSTEM

4.1 SUPPLY CHAIN DISRUPTIONS

Supply chain risks can generally be categorized in four types according to their frequency of occurrence and consequence: low probability & low impact (LPLI), low probability & high impact (LPHI), high probability & low impact (HPLI), and high probability & high impact (HPHI). Among them, LPHI risks are called disruptions. Figure 10 shows some examples of the risks to a company organized into those four groups.

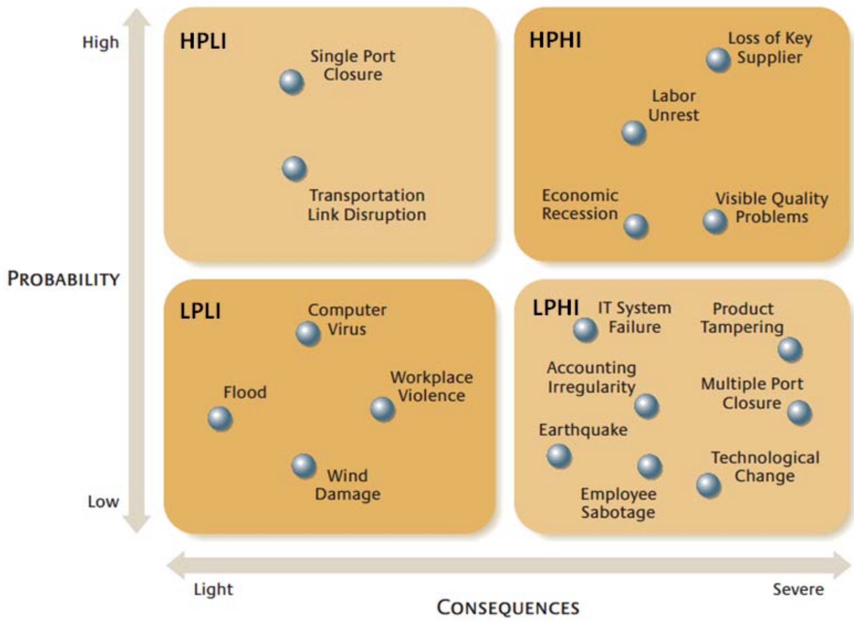

Figure 10: Four types of risks in a single company (Sheffi and Rice, 2005)

As supply chain disruptions are unplanned and unanticipated events that disrupt the normal flow of goods and materials (Kleindorfer and Saad, 2005), the whole supply chain/network is not fully prepared for the disruption and the disruption will directly lead to one or more of these capacity losses[3]:

- Capacity to acquire materials (supply)

[3] James B Rice, J. (2011). "The Japan Disaster: What Lessons Learned for the Supply Chain?". from http://www.cts.cv.ic.ac.uk/documents/seminars/cts_seminar270.pdf (accessed on Oct. 16 2012).

- Capacity to ship/transport
- Capacity to communicate/Information system
- Capacity to convert (internal operations)
- Availability of human resources (personnel)
- Financial flows (e.g. demand)

Generally, for a focal company, the recovery from disruptions depends on the company's ability to find the back-up capacity in the supply chain before its inventory is used up. This back-up capacity either has been built up before hand as the focal company's effort to fill resilience into its supply chain or just exists across supply chains as the excess capacity of other entities. However, the overall back-up capacity generally is not enough to cover the losses as disruptions by definition belong to the type of risk that is not fully prepared by supply chain entities. Thus companies will fight for the scarce back-up resources and the results will depend on the follows.

- The ability to sense the disruption and react promptly
- Pre-deployment of resources and relationship with other supply chain partners
- Comparative competitiveness in the interactions with others in a disruptions

Thus, it is necessary for a company to know the disruption propagation/cascading effects and understand the effects of the interactions among the supply chain entities both before and upon the occurrence of a disruption.

4.2 DISRUPTION PROPAGATION/CASCADING

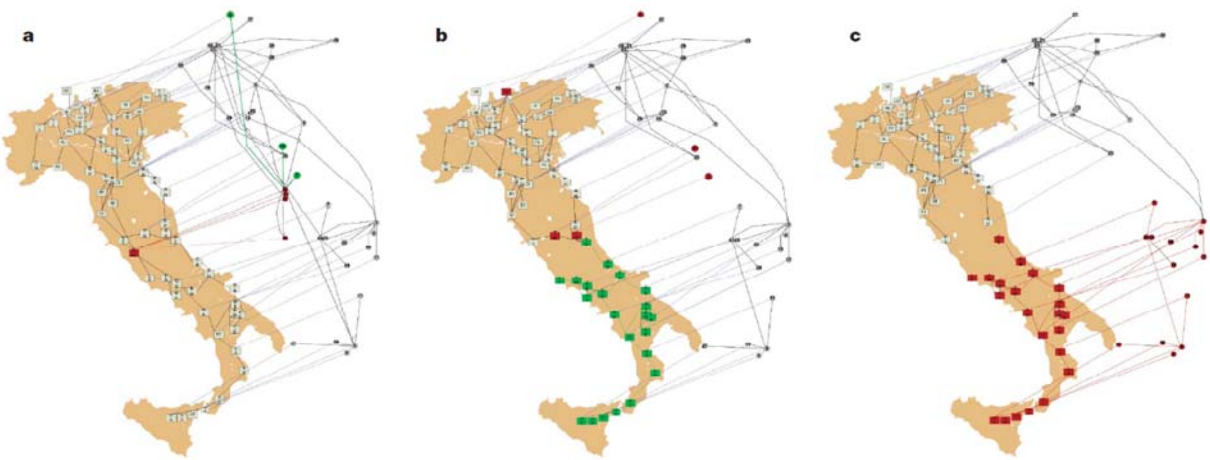

Figure 11: Catastrophic cascade of failures (Buldyrev et al., 2010)

Figure 11 illustrates an iterative process of a cascade of failures using real-world data from a power network (located on the map of Italy) and an Internet network (shifted above the map) that were implicated in an electrical blackout that occurred in Italy in September 2003 (Buldyrev et al., 2010).

In picture a, one power station is removed (red node on map) from the power network and as a result the Internet nodes depending on it are removed from the Internet network (red nodes above the map). The nodes that will be disconnected from the giant cluster (a cluster that spans the entire network) at the next step are marked in green.

In picture b, additional nodes that were disconnected from the Internet communication network giant component are removed (red nodes above map). As a result the power stations depending on them are removed from the power network (red nodes on map). Again, the nodes that will be disconnected from the giant cluster at the next step are marked in green.
In picture c, additional nodes that were disconnected from the giant component of the power network are removed (red nodes on map) as well as the nodes in the Internet network that depend on them (red nodes above map).

The propagation of a supply chain disruption can have similar effects as impacts can be passed on across supply chains/networks of different types (material, information, and finance) or of different industries. From a supply chain/network perspective, the relative positions of the individual firms with respect to one another influences the path of propagation. In this context, it becomes imperative to study each firm's role and importance as derived from its embedded position in the broader relationship structure. For example, Burkhardt and Brass (1990) claim that power and influence derive from a firm's structural position in its surrounding network.

4.3 DISRUPTION MITIGATION INTERACTIONS

The mitigation approaches listed in section 0 can be implemented by a company to improve its ability to counter risks at a supply chain level as the focal company's sole efforts subject to the constraint in its investment. However, the effects of those efforts may not be enough to cover certain risks, which involve interactions from multi-parties. From the risk framework developed in Figure 9, three types of such risks can be identified: relationship risk at the supply chain level, competitive and cluster substitution risks at the industrial level.

Relationship risk originates from the gap between a supply chain entity's actual importance and its assumed importance to its partner. For example, there are four types of supplier relationships (Bensaou, 1999) according to the investment to the relationship by a buyer and a supplier: captive buyer, strategic partnership, market exchange, and captive supplier (Figure 12). If a buyer thinks that its supplier is a captive supplier to itself (e.g. the buyer is more important to the supplier than the supplier is to the buyer) while the fact is that its supplier is only a market exchange partner to the buyer, the misconception will cause the buyer trouble when a disruption occurs and the supplier can easily cease supplying.

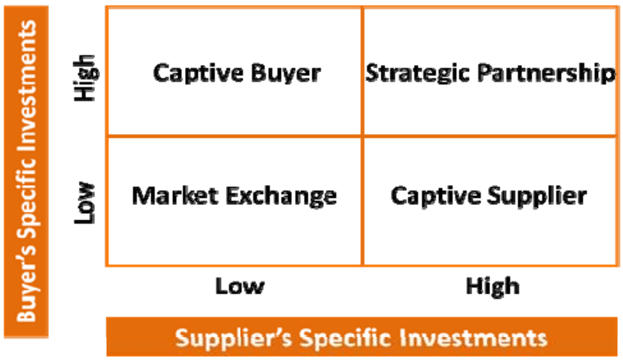

Figure 12: Types of buyer-supplier relationship (Bensaou, 1999)

The mitigation of the relationship risk requires a supplier/buyer's pre-disruption preparation and post-disruption reactions. Pre-disruption preparation includes the investment in the relationship to change the buyer-supplier relationship profiles. However, the final relationship may not be decided by only one side as the other side may at the same time change its status or investment in the relationship. For example, although Google may wish its Google Map application to be continuously used in iPad and iPhone, Apple prefers to its own map application in its latest launch of iPhone 5.

Post-disruption reactions are similar to those involved for competitive risk as a disappointed buyer/supplier needs to find alternative suppliers/buyers. The details will be discussed in the following section.

Competitive risk occurs when multi-entities are competing for scarce resources and is described in section 0. Hopp et al. (2008) proposed generic strategies that consist of two stages: (*i*) *preparation,* which involves investment prior to a disruption in measures that facilitate quick detection of a problem, and (*ii*) *response,* which involves post-disruption purchase of backup capacity for a component whose availability has been compromised. In both stage there exists competition from all entities.
In the pre-disruption stage, plants invest in preparedness and thereby determine their probabilities of being the first to detect a disruption. Hopp et al. (2008) show through game

theory that a unique Nash Equilibrium exists for each plant, which describes the preparedness investment for the market.

In the post-disruption stage, plants make purchases of backup capacity considering their production capacity and trying to maximizing profit from both short term sales and long term sales. Hopp et al. (2008) show that an optimal back-up capacity purchasing policy exists.

The observations of interactions among supply chain entities for competitive risk are as follows.

- When an entity makes a decision, it has to consider the status of its competitors and predict their possible decisions.
- The effects of a decision are affected by the decisions from other entities.

Thus, the behavior of an entity and the behavior of the system should be observed in the context of a complex system.

Cluster substitution risk is an expansion of competitive risk as more competitors are looking for alternative suppliers. However, the interactions among the competitors are similar to those in the mitigation for competitive risk.

The mitigation interactions for three types of disruptions are identified to be further studied in the context of complex systems in order to find best solutions for the individual supply chain entity and the overall supply network.

5. CONCLUSION

This white paper first develops a supply chain risk framework, which extends the current widely adopted framework by identifying that the impact and mitigation reactions of risks can be categorized into three levels: supply chain, industry, and macro. At the supply chain level, the impact of a risk is within a supply chain and the mitigation action involves only the focal company or between this company and its partners within the same supply chain. At the industry level, the impact of a risk is within the supply chains of the same industry; mitigation actions involve interactions and the results are not necessarily decided by one company. At the macro level, the impact of a risk may cross both industries and supply chains and a risk can propagate or cascade from one supply chain to another one. The mitigation actions involve many interactions and results are beyond the control of any single entity.

The framework also enables the identification of several risks, which demand mitigation interactions at different levels of scope. The results of those interactions become less predictable as the scope level increases from the supply chain level to the industry level, and on to the macro level. This is because a supply chain is actually a complex system, where the simple interactions among the entities may generate totally unexpected system level behaviors. Companies need to realize this fact and develop more efficient risk management systems.

Furthermore, the understanding of the complexity of a supply chain network can also help companies to know how a risk can propagate along the supply chains. The knowledge of this can facilitate the development of a detecting/monitoring system for sensing emergence of a risk at an early stage.

Finally, supply chain risks are further categorized into four types according to their occurring probability and severity of impact. Disruption propagation and mitigation interactions are discussed as examples of applying complex system concepts to supply chain risk management. The benefits of this approach are also summarized.

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