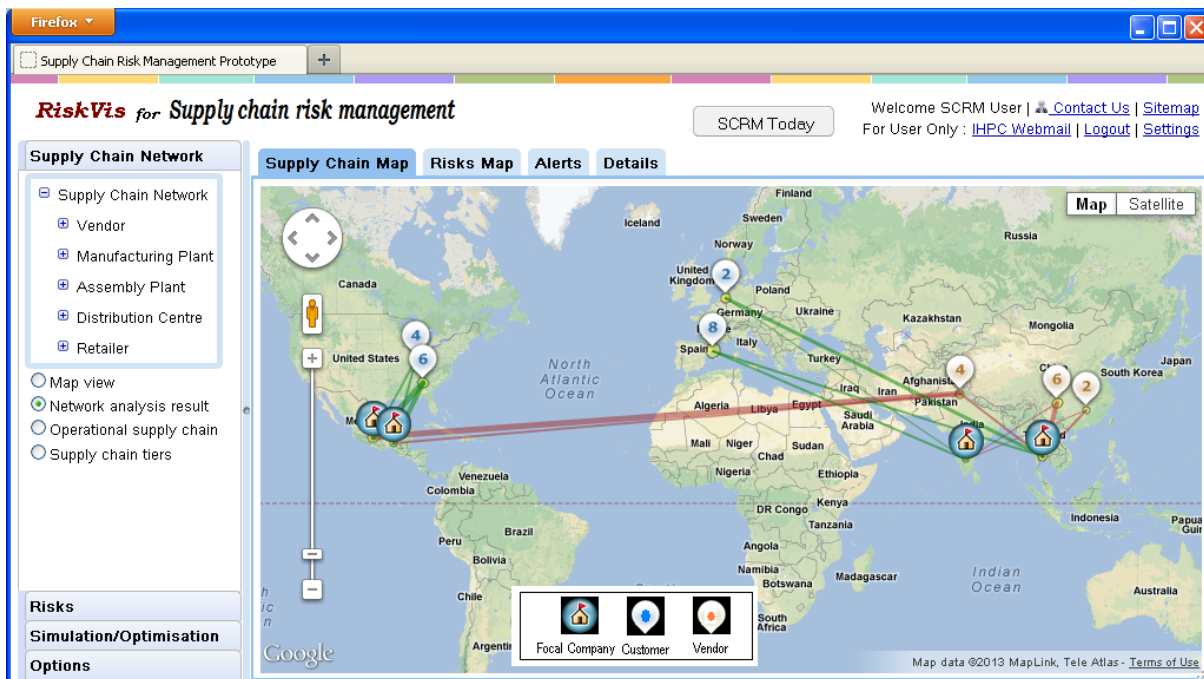


Advances in Supply Chain Risk Analysis

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Advances in Supply Chain Risk Analysis



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EXECUTIVE SUMMARY

The Supply chain risk is any event that disrupts the flow of materials/service on their journey from initial suppliers through to final customers (Waters, 2011). Supply chain risk management is thus the systematic identification, assessment, and mitigation of potential supply chain disruptions. In the current study, we present some advances in supply chain risk assessment, which is related to two factors: the disruption profile of the company where a risk occurs and the propagation of the disruption from the company across the whole supply chain. The first section is devoted to the assessment of risk impacts to supply chain partners and the second section identifies the factors that can be used to measure risk exposure of a company.

I. THE ASSESSMENT OF SUPPLY CHAIN RISKS

1. Problem Statement

In this section, we study how a company can systematically assess the impacts a risk can cause both to itself and to the supply network it is imbedded to.

2. Approach

2.1 Disruption Profile

Although Sheffi and Rice (Sheffi and Rice, 2005) identifies eight typical stages of disruption which include preparation, the disruption event, first response, initial impact, full impact, preparation for recovery, recovery, and long-term impact, we group those stages into two categories: decay and recovery.

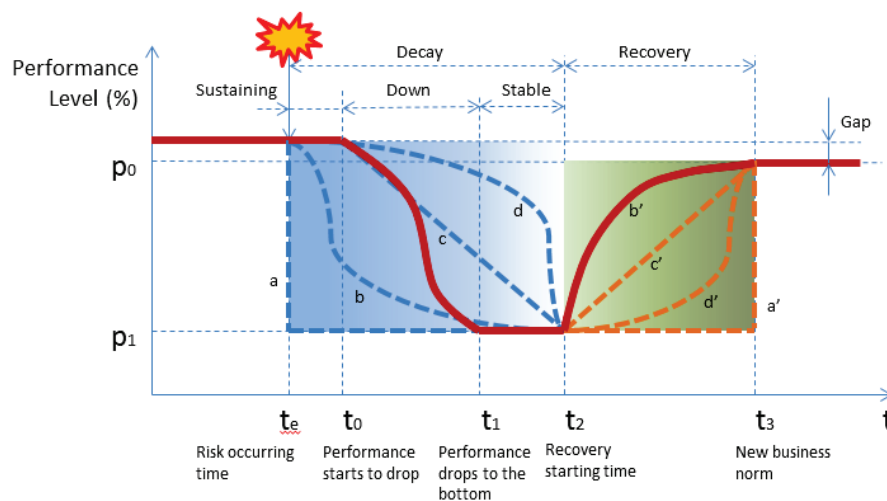


Figure 1. A generic disruption and recovery curve

Figure 1 refers to a generic disruption profile which tracks the performance or the yield level of a company from time t_e to t_3 . After a risk occurs at time t_e , the yield of a company may be sustained for a while till time t_0 ; then it starts to drop to the bottom at time t_1 . The yield level may stay at this bottom (p_1) for some time and then the recovery starts at time t_2 . A new business norm would be reached at time t_3 and the new yield level (p_2) of the company after the risk may be lower than the one before the risk (p_0).

In both stages of decay and recovery, there can be typically four types of decay/recovery patterns: abrupt, slow, normal, and fast. For example, decay patterns a, b, c, and d represent abrupt, slow,

normal, and fast decay in yield/performance, respectively; similarly, decay patterns a' , b' , c' , and d' represent abrupt, slow, normal, and fast recovery, respectively (Figure 1).

Therefore, two types of disruption profiles can be generated for companies with good robustness and resiliency and for those do not have. The robustness means that a company shows an acceptable performance in its Key Performance Indicators (KPIs) during and after a disruption event. The resiliency refers to the company's ability to recover to the previous performance after disruptions.

Figure 2 shows the disruption profile of a robust and resilient company. The company's yield sustains for some time then starts to drop slowly to the bottom till time t_2 ; it immediately recovers at time t_2 along a fast curve and then reaches a new norm at time t_3 . On the contrary, in Figure 3, a company's yield abruptly drops to the bottom right after the occurrence of a risk. It stays at the bottom until time t_3 for an abrupt recovery to a new norm. This company is fragile in facing a disaster and rigid in recovering back to a new norm.

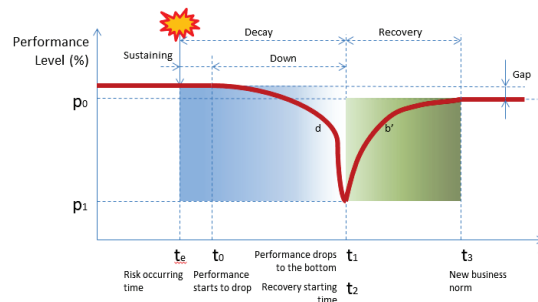


Figure 2. A disruption file of robustness and resiliency

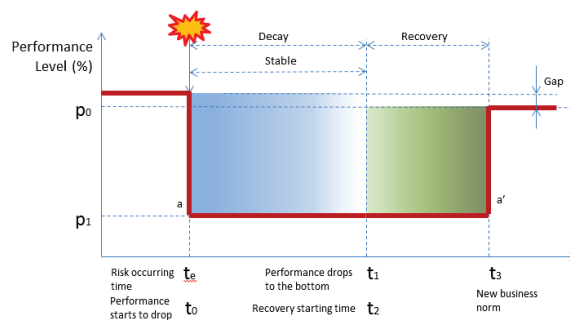


Figure 3. A disruption profile of no robustness and resiliency

2.2 Risk Propagation

Figure 4 is a generic supply chain with a focal company P1. We assume a tier one supplier S1.2 is hit by a disaster. The effects of the disaster can be passed on both upward and downward along the links starting from node S1.2.

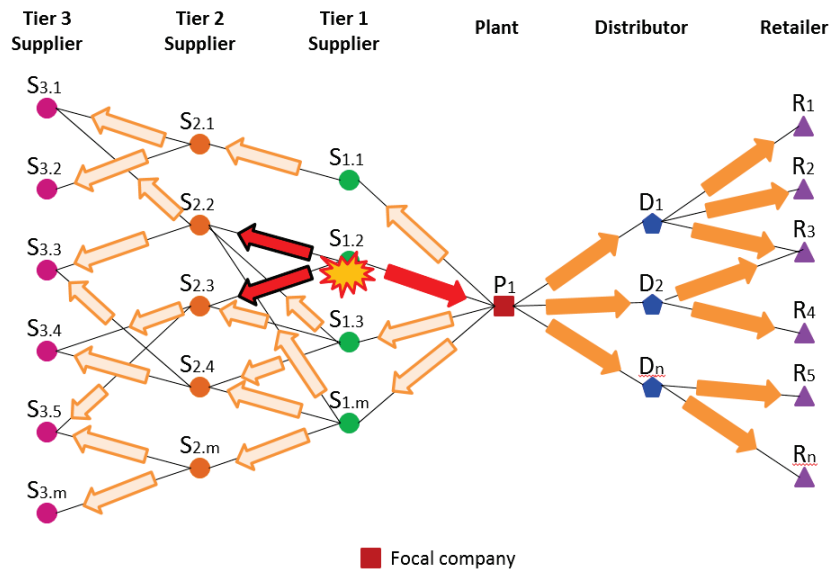


Figure 4. A generic supply chain with a focus company

We can observe that all nodes in the whole network are affected whenever one of them is under disruption through propagation. However, the disruption effect may be alleviated or reinforced along the way due to robustness and resiliency of nodes in the network.

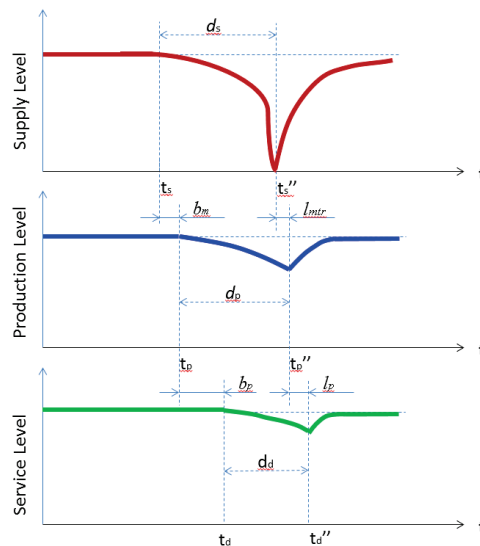


Figure 5. Disruption effect is alleviated in a robust and resilient supply chain

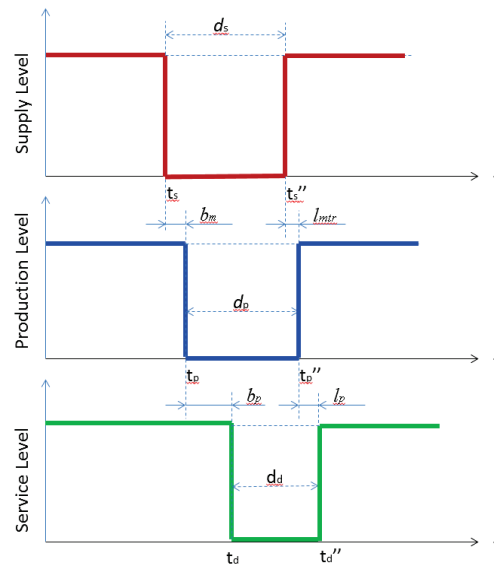


Figure 6. Disruption effect is reinforced in a fragile and rigid supply chain

For example, assuming nodes $S_{1,2}$, P_1 , and D_2 represent robust and resilient companies with disruption profiles similar to the one in Figure 2. Figure 5 shows a disruption occurred in supplier $S_{1,2}$ is actually alleviated when it is passed down from nodes $S_{1,2}$, P_1 , to D_2 . In contrary, if all those nodes are fragile and rigid to the other end, Figure 6 shows that the disruption in nodes $S_{1,2}$ is can be reinforced through nodes P_1 and D_2 .

3. Risk Evaluation

a) For the disaster attacked company

The impact of the disaster to the attacked company very much depends on the robustness and resiliency of the company. The disruption profiles are possibly varied between Figures 2 and 3. We can then use VaR (Value at Risk) or simulation to quantify the disruption impact.

VaR is widely used in the areas like banks, securities firms, commodity merchants, energy merchants, and other trading organizations (Zhang et al., 2012). VaR is defined as a threshold value describing the amount of loss that will not be exceeded within a certain period of time and under a certain probability (Jorion, 2007). It is a predictive (ex-ante) tool used to qualify the threshold value. Following data are required to qualify the disruption.

- The pattern of the disruption profile/distribution
- The occurring time of disruption
- The duration of the disruption
- The daily recovery cost of the company
- The mean and the standard deviation of the risk variable

Simulation enables companies to analyse and evaluate their systems’ performance in the occurrence of risks. A simulation model has to be built for the company based on its operational data. Generally, following data are required.

- The pattern of the disruption profile/distribution
- The occurring time of disruption
- The duration of the disruption
- Operational data e.g. inventory level, product unit cost, demand, etc.

b) For the affected companies

For those companies that are affected through risk propagation, e.g. focal company P1, and distributor D2, their disruption profiles can be illustrated in Figure 7 in a time series. We assume that the focal company adopts the make-to-order strategy and thus does not keep the product inventory.

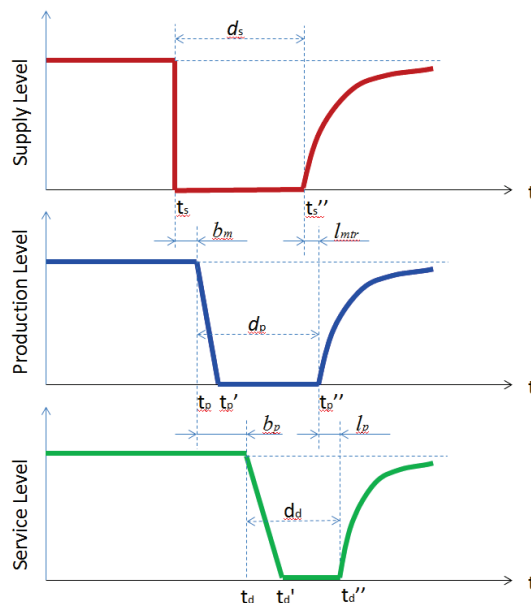


Figure 7. Risk propagation from supplier, manufacturer to distributor

The generic scenario is given assuming that supplier $S_{1,2}$ is hit by a disaster at time t_s and its yield drops to the bottom immediately. Manufacturer P_1 sustains its production for some time (b_m) buffered by its material and pipeline inventories till time t_p before its production level drops to the bottom. Similarly, the distributor D_2 sustains its service level for some time (b_p) buffered by its product inventory till time t_d . The service level starts to drop at time t_d and then reaches to the bottom at time t_d' .

For manufacture P1, the occurring time of the disruption (t_p) and duration (d_p) can be calculated as follows.

$$t_p = t_s + b_m \tag{1}$$

$$d_d = d_s - b_m + l_{mtr} \tag{2}$$

Similarly, for distributor D2, the occurring time of the disruption (td) and duration (dd) are:

$$t_d = t_s + b_m + b_p \tag{3}$$

$$d_d = d_s - b_m - b_p + l_{mtr} + l_p \tag{4}$$

Where l_{mtr} and l_p refer to the transportation lead times from the supplier to the manufacturer and from the manufacturer to the distributor, respectively.

Thus, the disruption triggered by supplier S1.2 to focal company P1 and distributor D2 can be qualified using the basic approaches in section a. In this way, the effect of the disruption to the rest of the nodes in the network can be obtained similarly.

a. For the whole supply chain

Based on the calculations in sections a and b, the impact triggered by the disaster on supplier S1.2 to each node can be listed out. Then its overall impact on the supply chain network can be summed up. Furthermore, a risk effect matrix can be built as in Table 1.

Disruption Origin Node	Node 1	Node 2	Node 3	Node 4	...	Node n	Overall Impact
Node 1	$l_{1.1}$	$l_{1.2}$	$l_{1.3}$	$l_{1.4}$	...	$l_{1.n}$	l_1
Node 2	$l_{2.1}$	$l_{2.2}$	$l_{2.3}$	$l_{2.4}$	...	$l_{2.n}$	l_2
Node 3	$l_{3.1}$	$l_{3.2}$	$l_{3.3}$	$l_{3.4}$	...	$l_{3.n}$	l_3
Node 4	$l_{4.1}$	$l_{4.2}$	$l_{4.3}$	$l_{4.4}$	...	$l_{4.n}$	l_4
...
Node n	$l_{n.1}$	$l_{n.2}$	$l_{n.3}$	$l_{n.4}$	...	$l_{n.n}$	l_n

Table 1. Risk effect matrix

From the table, we can identify the critical node which has the greatest impact to each node and to the overall supply chain network. For example, $l_{1.3}$ is the qualified value of the effect of node 1 to node 3. From the column of Node 3, through the list of values, e.g. $l_{1.3}$, $l_{2.3}$, ... to $l_{n.3}$, if $l_{4.3}$ is the greatest value in the column, then node 4 among all the node in the network has the biggest effect on node 3. This means node 4 can cause biggest disruption to node 3. Similarly, we may identify which node could cause biggest disruption to the overall supply chain network.

4. Benefits

The current study first identify that in order to qualify the impact of a disaster to any node in a supply chain network, we need to know 1) how to calculate the risk impact based on the disruption profile of the node and 2) how the disruption propagates across the network. We then propose the way to evaluate the impacts of a disaster to the original node, to the directly and non-directly affected nodes, and to the overall supply chain network. Finally, an example is given to illustrate how the qualified disruption impacts can enable systematic identification of critical nodes to each node and to the whole network.

II. RISK ASSESSMENT – CONNECTEDNESS APPROACH

1. Problem statement

Since an entity is a part of the supply chain network and decision makers typically have insufficient knowledge to cope with the unexpected disruption events, the disruption would be propagated to other entities. Thus, an entity requires identifying the potential disruption caused by risks as well as the potential sources of the risks considering its supply chain network.

2. Our Approach

As we define the disruption is the realized (compound) risk regardless of the type and the level in this article, the risk influences indirectly on the entity's performance whereas the disruption has the direct influence. In this sense, it is worth to notice that there is a gap between risk and disruption. The concept of influence factors is introduced to bridges the gap between risk and disruption (Section II.1). As the influence factors reflect the status of an entity against to potential risk, the factors provide useful knowledge to diagnose the internal level of disruption (Section II.2). In addition, when the partner entities share their knowledge by building the strong business relationship with each other, they would refer to the influence factors belonging to their partner entities so that they estimate the potential disruption from the partners (Section II.3).

2.1 Influence factors

An entity contains various factors directly influenced by risk, which would define the disruption of interest with its levels and types and eventually influences on the performance. We refer those factors to as influence factors. Each entity may have its own influence factors with variety and hierarchy and they are hard to be categorized due to the manageable characteristics. In the proposed framework, the influence factors are assumed to be generally classified and categorized into four groups, namely, Product, Demand, Supply, and Cluster. As shown in Figure 8, the influence factors have hierarchical structure. When a risk is realized in the entity, some parts of influence factors are triggered by the risk. Several factors belonging to different categories (e.g., Product and Supply) are possibly triggered together. In this sense, on the other hand, the direct effect of risk can be interpreted by linking up the impact levels of influence factors against to the risk because the risk has only indirect effect and the influence factors triggered by the risk would generate the disruption that has the direct effect.

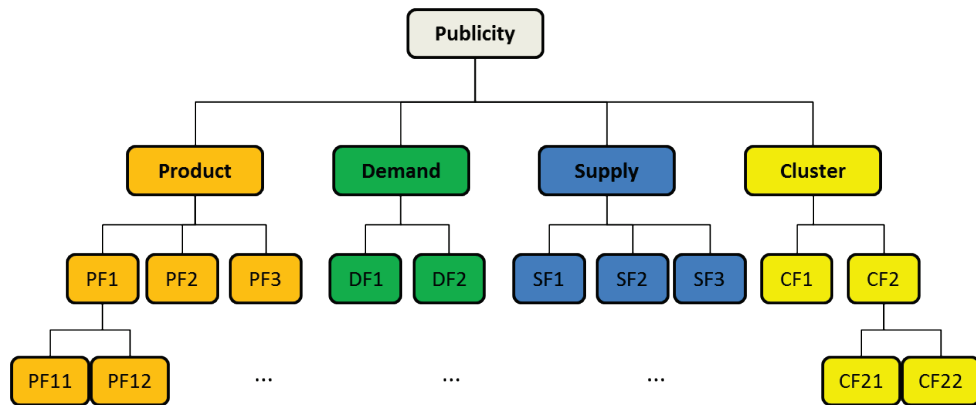


Figure 8. Variety and hierarchy of Influence factors

The values of influence factors would be estimated from the historical data and determined by the decision makers though it is subjective. Suppose that Product factor PF1 has been influenced by a certain set of risk realizations, the distribution for the risk realizations would represent PF1. Based on the distribution, the decision makers would determine the relative importance of PF1 comparing to others.

As the influence factors represent the potential disruptions, an entity may not expose the factors in the low levels. Instead, they may publicize the representative index for the influence factors, which is referred to as Publicity in Figure 8. However an entity would show lower level influence factors when it builds serious relationship with partners.

2.2 Self-disruption of an entity

Quantifying the level of the influence factors is critical to estimate the direct effect on the performance of the entity. The risk may actually come from the internal process of the entity or external events. Influence factors turn out to the disruption of the performance of the entity regardless of the causes of risk. Thus, we can use the influence factors to diagnose the self-disruption of the entity. The self-disruption is estimated by quantifying the impact level of the influence factors against to the potential risks.

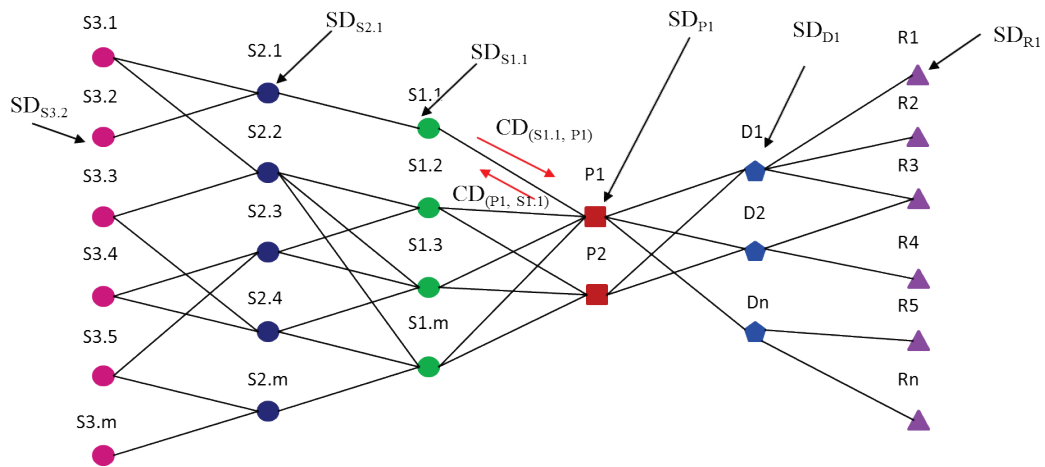


Figure 9. Supply chain risk framework

Figure 9 shows the supply chain risk framework that contains 3-tier suppliers, manufacturers, distributors, and retailers. The framework visualizes the potential disruption of each entity involving the supply chain network and the disruption relationship between entities. The self-disruption, depicted as SD_{P1}, for example, can be represented as the value of the entity P1 (manufacturer) in the framework. However, SD_{P1} would be estimated by investigating its own influence factors without considering the partner entities. Thus, it is recommended to estimate the index representing the relationship with each partner entity so that the index would explain disruption caused by interacting with partners.

2.3 Connectedness disruption between linked entities

On the supply chain risk framework (in Figure 9), there are two unidirectional arcs linking two entities P1 and S1.1, for example: one is from entity S1.1 to P1; and the other is from Entity P1 to S1.1. Thus, each arc represents the connectedness disruption with directionality from an entity to the other. For P1 an S1.1, the connectedness risks are denoted as $CD_{(S1.1, P1)}$ and $CD_{(P1, S1.1)}$, respectively. The connectedness disruption is a view of the potential risk on the influence factors of an entity by considering the exposure level of risk on the influence factors of the partner entity. Thus, connectedness disruption would have different values for different partner entities as those may have different values of influence factors or different exposure levels of risk. In order to estimate the connectedness disruption, it is required to estimate the effect of the influence factors for Entity S1.1 on those for Entity P1 or vice versa.

Suh (2001) invented a functional design methodology by sequentially mapping the requirement of one domain to another. The author determined the design requirement from the relationship between two domains though the measurement is possibly subjective. We borrow the idea to estimate the connectedness disruption of an entity by referring to the influence factors of the other entity. Figure 10 explains how we refer the influence factors from one side to the other. It is assumed that the two entities share the same level of knowledge when they build relationship to enhance the

interaction/trades and to help preparing potential disruptions. According to Myers and Cheung (2008), knowledge sharing is recommended even though the knowledge sharing may be controversial.

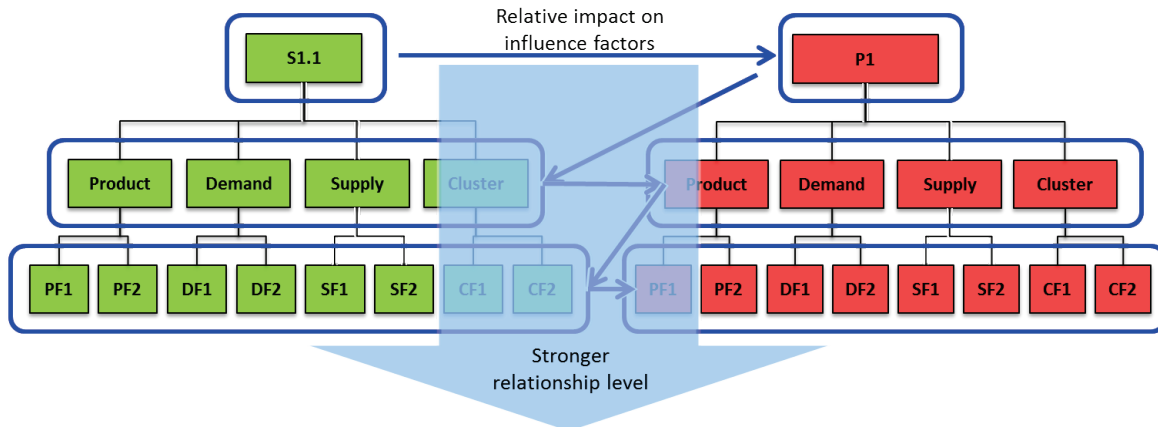


Figure 10. Mapping influence factors of a supplier (S1.1) for a manufacturer (P1)

Figure 10 gives us an example to estimate the connectedness risk from the influence factors of the two entities, S1.1 and P1. When the two entities build serious relationship, they share the knowledge regarding the influence factors to that decision makers may be able to anticipate the potential disruption for the partners. From the perspective of S1.1, in Figure 3, it only obtains connectedness disruption from the public knowledge provided by P1 if they do not share the knowledge regarding influence factors. However, their relationship gets stronger, they share more knowledge for their influence factors and the decision makers in S1.1 possibly map their influence factors to those provided by P1. By integrating the impacts on the influence factors against to those of a partner entity, the connectedness risk would be determined. The estimated connectedness risk is depicted on arcs in the supply chain risk framework in Figure 9.

3. As is

Much research has been conducted to identify the firm risk. (Chopra and Sodhi, 2004) categorized the supply chain risks (Disruptions, Delay, Systems, Forecast, Intellectual Property, Procurement, Receivables, Inventory, and Capacity) and the drivers of each risk with examples. The authors also provided mitigation approaches and the impact of mitigation strategies on the risks as well as other mitigation strategies. (Sheffi and Rice, 2005) introduced the disruption profile that describes the stages of disruption, and proposed two ways (redundancy and flexibility) for increasing resilience which is the ability to be against to threats and occurrence of supply chain disruptions.

As the supply chain risk has the subjective nature in terms of perception of decision makers, which means that different decision makers identify and assess a risk in different ways or levels. The professionalism of decision makers may not be often helpful to judge the risk. According to (Tazelaar

and Snijdersb, 2013), the net effects of the specialized and general expertise on the assessment performance are negligible. The authors recommended that the risk assessment may benefit from less reliance on intuitive judgment, an increase in feedback on the correctness of previous assessments, and the involvement of model-based prediction in the assessment process. (Zsidi and Wagner, 2010) examined the relationships between the supply chain risk perception and disruption occurrence, and between the resiliency practices and the effect of supply disruptions through conducting the factor analysis on the empirical data collected from various industries. According to their findings, supply managers will implement measures that go beyond what is necessary given the true likelihood of occurrence of disruptions stemming from supply chains. Thus, the higher the perception of a risk source, the firm will experience the effects of supply disruptions less frequently caused by supply chains. Other than identifying risk by decision makers, (Neiger et al., 2009) proposed a risk identification methodology based on the value-focused processing engineering, through viewing a supply chain as a set of interconnected value-adding processes, risk reduction as business objectives, and risk sources. However, (Olson, 2012) recommended expressing the risk exposure levels in symbolic ways such as words and colors according to the severity and the frequency due to the investigation that the numerical expression is not significant to identify it. In addition, less variant symbolic expressions are helpful to decision makers to understand the risk exposures.

(Ghemawat and Altman, 2012) developed and reported the global connectedness index of a country with the rest of the world. The global connectedness index consists of depth and breadth metrics manifested by the participation in international flows of products and services, capital, information, and people. In addition, the index provides the directionality of outward and inward flows between countries. The work of (Ghemawat and Altman, 2012) is applicable to supply chain network to identify the risk influence when each entity has its own profile influencing other entities.

Recently, some studies have been considered to identify the potential risk under the relationship with partner entities. (Mizgier et al., 2012) studied the dynamics of behaviors of the supply chain network under uncertain environment using the agent based modeling approach. The objective is to observe the propagation effect of a local default for a firm on the global performance of the supply chain network, in which the financial default occurs when the working capital of a firm hit the threshold level that is a fraction of the average working capital of all firms, and the performance measure is the percentage of the working capital utilized in production of the whole system at a certain time. (Mizgier et al., 2013) studied a way for a focal firm to identify high-risk suppliers (potential bottlenecks) by estimating the loss distribution due to the hazard events via Monte Carlo simulation in supply chain networks. The loss contribution represents reduction in production in percentage terms and per time unit. The proposed loss distribution approach estimates the propagation of hazard events and is superior in favor of considering the features of the network structure to identify the potential risky suppliers to other social network approaches. The authors considered a focal firm and suppliers in the network and the hazard events are generated from suppliers. As the interaction between firms was represented by the loss contribution, a simulation-based approach is used to estimate the loss impact of a supplier to the total average loss of the focal firm.

4. Novelty

The proposed supply chain risk framework considers the self-disruption of an entity as well as the connectedness disruption from direct partners. Unlike (Mizgier et al., 2012), the risk framework represents disruption level using the index estimation model rather than simulation based approach. The index representation provides quick and intuitive response for the potential disruption though the simulation can analyze the results in detail. (The efficient update – quick fix – of supply chain network is appeared in Chapter 7.) The connectedness approach estimates the disruption index in a cascading way, thus, this approach also possibly provides the partial view of the supply chain network by cutting a certain set of entities in the network. Unlike (Mizgier et al., 2013), our approach do not fix the focal firm. As described earlier, the disruption index would be determined in a cascading way by only referring to the direct partners. Thus, each entity becomes a focal firm when its disruption index is determined. The approach of (Mizgier *et al.*, 2013) considered a supply chain network in which the interaction is represented by the percentage of loss contribution and similarly the connectedness approach uses the influence factors. However, the influence factors represent the potential disruptions of both internal and external effects from risk events. In such a way, the influence factors contain the loss distribution when they are determined. Therefore, the risk framework is constructed analytically, produces disruption index of each entity, which has its own thresholds for the self-disruption and the connectedness disruption, and eventually improve the resilience of the supply chain network by estimating the potential disruption.

5. Benefits

A new definition of risk for an entity can be defined by estimating potential disruption level from both internal and external disruptions based on influence factors. The new risk index would be beneficial to evaluate the current risk level, provide a chance for improving the resilience, or re-coordinate the supply chain network. It means that we can define the risk index as

$$R_{p1} (\text{Risk}) = SD_{p1} (\text{self-risk}) + \sum_{i \in C} CD_{(i,p1)}$$

Note that C is the set of arcs connected to the focal entity, SD is the self-disruption, and CD is the connectedness disruption directing to the focal entity. The risk index consists of the self- disruption and the connectedness disruption from direct partner entities. The proposed risk index has advantages to coordinate/design the supply chain network in the view of reducing potential disruptions.

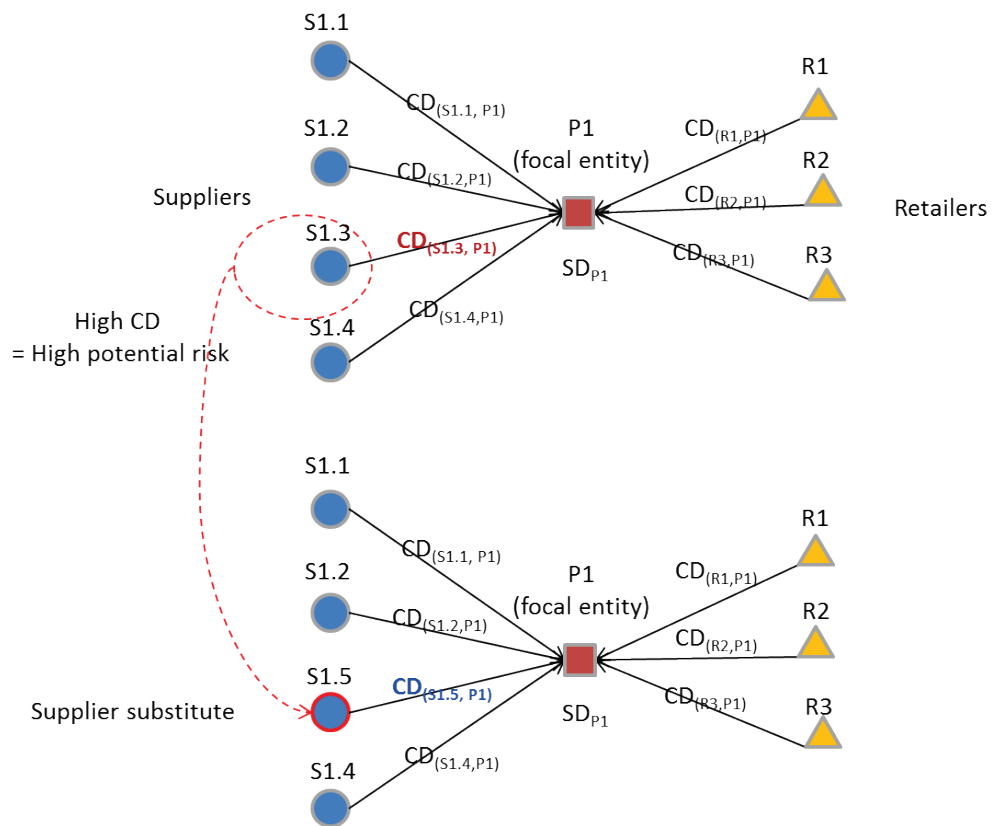


Figure 11. Supply chain coordination using the risk exposure index

When the focal entity P1 judges that a supplier has great expected risk exceeding a certain threshold to cause disruptions, for example, the entity may be able to substitute the supplier S1.3 as drawn in Figure 11. Through this activity, the supply chain is redesigned and the supply chain risk framework would be updated by referring to CD provided by the new supplier S1.5. The proposed risk framework provides a systematic way to help each entity visualize the potential disruption by estimating its own disruption level as well as the connectedness disruption caused from its partner entities. The risk framework would not be helpful to only evaluate the risk level but also applicable to design the supply chain network.

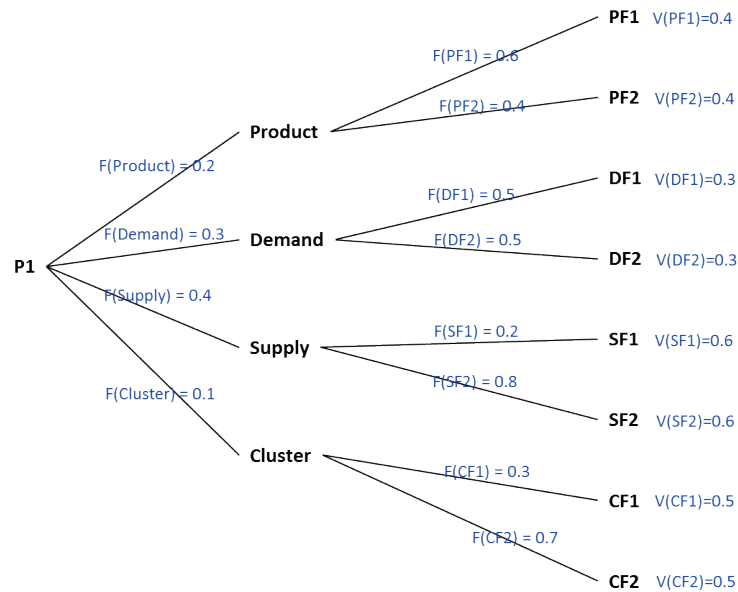
Appendix. Explanatory example

By using Figures 10 and 11, we draw an explanatory example to elaborate the proposed risk framework. It is assumed that $CD_{(S1.1,P1)}=0.4$, $CD_{(S1.2,P1)}=0.4$, $CD_{(S1.4,P1)}=0.2$, and $CD_{(R1,P1)}=CD_{(R2,P1)}=CD_{(R3,P1)}=0.5$. Knowing that the index for either the self-disruption (SD) or the connectedness disruption (CD) has between 0 and 1, the risk (R_{P1}) would have 8 as the maximum value in this particular example because the seven arcs are connected to the P1. It is set the threshold of P1 for a supplier is 0.5 and the threshold of R_{P1} is 5.

A.1 Estimating SD_{P1}

Estimating SD_{P1} is depicted as Figure 12. $F(PF1)$ means that the relative importance of the influence factor PF1 in the level. $V(PF1)$ is the value of influence factor PF1 in the level, which is estimated from the history data. All F and V values are assumed as shown in Figure 12. Thus,

$$SD_{P1} = (0.2 \times 0.5 \times 0.4) + (0.2 \times 0.4 \times 0.4) + \dots + (0.1 \times 0.7 \times 0.5) = 0.46$$



A.2 Estimating $CD_{(S1.3,P1)}$

Figure 13 enumerates partially the zigzag estimation procedure.

$$\begin{bmatrix} \text{Product}(P1) \\ \text{Demand}(P1) \\ \text{Supply}(P1) \\ \text{Cluster}(P1) \end{bmatrix} = \gamma \cdot \begin{bmatrix} \text{Product}(S1.3) \\ \text{Demand}(S1.3) \\ \text{Supply}(S1.3) \\ \text{Cluster}(S1.3) \end{bmatrix}$$

$$\begin{aligned}
 \begin{bmatrix} \text{Product}(S1.3) \\ \text{Demand}(S1.3) \\ \text{Supply}(S1.3) \\ \text{Cluster}(S1.3) \end{bmatrix} &= \delta_1 \begin{bmatrix} PF1(P1) \\ PF2(P1) \end{bmatrix}, \begin{bmatrix} \text{Product}(S1.3) \\ \text{Demand}(S1.3) \\ \text{Supply}(S1.3) \\ \text{Cluster}(S1.3) \end{bmatrix} &= \delta_2 \begin{bmatrix} DF1(P1) \\ DF2(P1) \end{bmatrix}, \begin{bmatrix} \text{Product}(S1.3) \\ \text{Demand}(S1.3) \\ \text{Supply}(S1.3) \\ \text{Cluster}(S1.3) \end{bmatrix} &= \delta_3 \begin{bmatrix} SF1(P1) \\ SF2(P1) \end{bmatrix}, \begin{bmatrix} \text{Product}(S1.3) \\ \text{Demand}(S1.3) \\ \text{Supply}(S1.3) \\ \text{Cluster}(S1.3) \end{bmatrix} &= \\
 & \delta_4 \begin{bmatrix} CF1(P1) \\ CF2(P1) \end{bmatrix} \\
 \begin{bmatrix} PF1(P1) \\ PF2(P2) \end{bmatrix} &= \varepsilon_1 \cdot \begin{bmatrix} PF1(S1.3) \\ PF2(S1.3) \end{bmatrix}, \begin{bmatrix} PF1(P1) \\ PF2(P2) \end{bmatrix} &= \varepsilon_2 \cdot \begin{bmatrix} DF1(S1.3) \\ DF2(S1.3) \end{bmatrix}, \dots
 \end{aligned}$$

Figure 13. Zigzag procedure for estimating CR

Note that the Greek letters such as γ , δ , and ε are explanatory matrices to define the relationship between two sets influence factors. Those relationships have hierarchy structure summarized as Figure 8.

$$\begin{bmatrix} \text{Product}(P1) \\ \text{Demand}(P1) \\ \text{Supply}(P1) \\ \text{Cluster}(P1) \end{bmatrix} = \gamma \cdot \left\{ \begin{array}{l} \delta_1 \cdot \begin{bmatrix} \varepsilon_1 \cdot \begin{bmatrix} PF1(S1.3) \\ PF2(S1.3) \end{bmatrix} \\ \varepsilon_2 \cdot \begin{bmatrix} DF1(S1.3) \\ DF2(S1.3) \end{bmatrix} \\ \varepsilon_3 \cdot \begin{bmatrix} SF1(S1.3) \\ SF2(S1.3) \end{bmatrix} \\ \varepsilon_4 \cdot \begin{bmatrix} CF1(S1.3) \\ CF2(S1.3) \end{bmatrix} \end{bmatrix} \\ \delta_2 \cdot \begin{bmatrix} \varepsilon_5 \cdot \begin{bmatrix} PF1(S1.3) \\ PF2(S1.3) \end{bmatrix} \\ \varepsilon_6 \cdot \begin{bmatrix} DF1(S1.3) \\ DF2(S1.3) \end{bmatrix} \\ \varepsilon_7 \cdot \begin{bmatrix} SF1(S1.3) \\ SF2(S1.3) \end{bmatrix} \\ \varepsilon_8 \cdot \begin{bmatrix} CF1(S1.3) \\ CF2(S1.3) \end{bmatrix} \end{bmatrix} \\ \delta_3 \cdot \begin{bmatrix} \varepsilon_9 \cdot \begin{bmatrix} PF1(S1.3) \\ PF2(S1.3) \end{bmatrix} \\ \varepsilon_{10} \cdot \begin{bmatrix} DF1(S1.3) \\ DF2(S1.3) \end{bmatrix} \\ \varepsilon_{11} \cdot \begin{bmatrix} SF1(S1.3) \\ SF2(S1.3) \end{bmatrix} \\ \varepsilon_{12} \cdot \begin{bmatrix} CF1(S1.3) \\ CF2(S1.3) \end{bmatrix} \end{bmatrix} \\ \delta_4 \cdot \begin{bmatrix} \varepsilon_{13} \cdot \begin{bmatrix} PF1(S1.3) \\ PF2(S1.3) \end{bmatrix} \\ \varepsilon_{14} \cdot \begin{bmatrix} DF1(S1.3) \\ DF2(S1.3) \end{bmatrix} \\ \varepsilon_{15} \cdot \begin{bmatrix} SF1(S1.3) \\ SF2(S1.3) \end{bmatrix} \\ \varepsilon_{16} \cdot \begin{bmatrix} CF1(S1.3) \\ CF2(S1.3) \end{bmatrix} \end{bmatrix} \end{array} \right.$$

Figure 14. Hierarchy structure of the relationship for CD

$CD_{(S1.3, P1)}$ would be estimated by referring to Figure 15, where $E(\gamma)$ is the evaluation of the explanatory matrix γ represented as a single value between 0 and 1. In this particular example, we assumed the values are as shown in Figure 15. Hence, $CD_{(S1.3, P1)} = 0.56$. Therefore, R_{P1} becomes 3.52 and is less than the threshold. However, $CD_{(S1.3, P1)} = 0.56$ is greater than the supplier threshold (0.5). If P1 substitutes S1.3 with S1.5, it would satisfy both thresholds due to the estimation that $CD_{(S1.5, P1)} < 0.5$.

$$CD_{(S1.3, P1)} = \text{Average} \left\{ \begin{array}{l} E(\gamma \cdot \delta_1 \cdot \varepsilon_1) = 0.7 \\ E(\gamma \cdot \delta_1 \cdot \varepsilon_2) = 0.5 \\ E(\gamma \cdot \delta_1 \cdot \varepsilon_3) = 0.1 \\ E(\gamma \cdot \delta_1 \cdot \varepsilon_4) = 0.6 \\ E(\gamma \cdot \delta_2 \cdot \varepsilon_5) = 0.7 \\ E(\gamma \cdot \delta_2 \cdot \varepsilon_6) = 0.5 \\ E(\gamma \cdot \delta_2 \cdot \varepsilon_7) = 0.2 \\ E(\gamma \cdot \delta_2 \cdot \varepsilon_8) = 0.8 \\ E(\gamma \cdot \delta_3 \cdot \varepsilon_9) = 0.5 \\ E(\gamma \cdot \delta_3 \cdot \varepsilon_{10}) = 0.2 \\ E(\gamma \cdot \delta_3 \cdot \varepsilon_{11}) = 0.9 \\ E(\gamma \cdot \delta_3 \cdot \varepsilon_{12}) = 0.4 \\ E(\gamma \cdot \delta_3 \cdot \varepsilon_{13}) = 0.7 \\ E(\gamma \cdot \delta_3 \cdot \varepsilon_{14}) = 0.8 \\ E(\gamma \cdot \delta_3 \cdot \varepsilon_{15}) = 0.7 \\ E(\gamma \cdot \delta_3 \cdot \varepsilon_{16}) = 0.6 \end{array} \right\} = 0.56$$

Figure 15. Estimating $CD_{(S1.3, P1)}$

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