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DESIGNING QUANTITATIVE METRIC FOR EVALUATING STRUCTURAL VULNERABILITY OF SUPPLY CHAIN CONSIDERING RISK PROPAGATION MODEL

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Abstract: *This paper is aim to develop the metric for assessing the vulnerability of supply chain network considering risk propagation. In this research, the betweenness centrality has been utilized to quantitatively assess the structural vulnerability. The betweenness centrality is interpreted as the metric which can express both the probability of risk occurrence and propagation of risk impact. Through the case study, we have reinforced the applicability of proposed metric. With the proposed vulnerability metric, it may be possible to compare the stability of each alternative supply chain structure and choose the better one.*

Keywords: *Supply Chain Risk Management, Risk Propagation, Structural Vulnerability.*

1. INTRODUCTION

The rapid change of global market structure as well as globalization and integration of supply chain make the supply chain itself face the more uncertainty. Also, it is hard to efficiently control and operate supply chain execution plans. Therefore, it is getting higher possibilities supply chains to face unexpected situation, so to speak, "RISK" (Royal Society Study Group, 1992). While defining the supply chain risk as "the unexpected factors which have negative impacts on the sustainability and feasibility of supply chain plans", it is necessary to develop the proactive methodologies which can mitigate the impact of supply chain risk factors and enhance the sustainability. In order to solve this problem, it has been suggested the coordination based approach such as wholesale quantity contract (Qi, Bard, & Yu, 2004; Intan, 2016). However, under the circumstances that several stakeholders are complicatedly connected, it is general that the adequate responses to the risk factors are late to proper time, and it is hard to recover from the disruption (You, Wassick, & Grossmann, 2009). Therefore, in order to make agile response to the market changes and requests from customers, it is necessary to predict the situation which the risk

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factors break out, and make the structure of supply chain be resilient to the disrupted situation in the phase of supply chain design. So to speak, it should be possible to evaluate how much the quantitative impacts that the risk factors have, how fast we can overcome the impacts when any suppliers are exposed to the risk factors. In order to do so, we need the quantitative criteria to evaluate the supply chain risk considering the network structure. It is general that the structures of supply chains are depicted with nodes, arcs and their linked relationship. Thus, it will be possible to analyze the supply chain structure by investigating the relationship among nodes and arcs. There exists a prior research to find and concentrate on managing the most important node (Wilson, 2007). In addition, there is other approach such as mitigating the impact from the risk by enhancing the flexibility of supply chain operation (Glenn Richey Jr, Skipper, & Hanna, 2009) and by keeping the back-up suppliers (Tang & Musa, 2011). Especially, it has been proposed to prove the relationship the structural characteristics of supply chain and risk factors, and to find the most important structural components based on this relationship (Nair & Vidal, 2011 Ramly & Omar, 2016). Still, there exist some limitations that the structural relationship is only considered and proved in the certain node where the risk factors occur. Therefore, to overcome the limitations, this research has suggested a novel approach to evaluate the structural vulnerability in terms of whole network, not the certain nodes. To model the structural relationship among nodes, we have adopted some concepts in Graph Theory and design the quantitative metric to evaluate the structural vulnerability.

The remainder of this paper is organized as follows: in the next section, we will introduce some prior research and present some limitations. In section 3, it will be explained the assumptions and procedure to build the quantitative metric for evaluating structural vulnerability. With the result of the numerical example, it will be explained how the proposed metrics is interpreted and utilized in section 5. Finally, we will conclude with some contributions and limitations of our research.

2. BACKGROUND AND RELATED WORK

In this section, it will be explained the background and fundamental concepts to understand the proposed approach.

Risk Propagation in Supply Chain

Generally, supply chains consist of cooperates which have partnership to supply raw materials, produce and utilize products or services (C. M. Harland, Lamming, Zheng, & Johnsen, 2001; Lamming, Johnsen, Zheng, & Harland, 2000). The structure of supply chain is modeled with the set of nodes and connected relationship among nodes and the relationship may have direction according to the flow of information, material, and monetary. Therefore, the supply chain risk of a certain node may have impact on the other connected nodes (Shin, Shin, Kwon, & Kang, 2012). Eventually, the impact of risk in a certain node can propagate to the whole network along the connected structure. Because of these characteristics of supply chain and supply chain risk, it is hard to manage risk itself. In addition, even though it is possible to control a certain risk factor, it may increase the other risk (Chopra & Sodhi, 2004).

Evaluation of Supply Chain Risk

It can be said that supply chain risk management (SCRM) is the procedure to make decision to predict, assess and react on the supply chain risk. This procedure may start from identifying, understanding, and modeling the supply chain risk. The fundamental objective of whole procedure is to minimize the impact of risks and reduce the probability of occurring risks.

It is general and widely accepted approach to model the risk or impact of risk with the probability and impact of risk, ($Risk_n = Pr(Loss_n) \times I(Loss_n)$) (Mitchell, 1995). Also, C. Harland, Brenchley, & Walker (2003) has suggested the framework to evaluate the risk of supply chain, which consists of six phases. With this framework, it is possible to enhance the visibility of supply chain risk and prepare the situation of occurring risk. However, the practical availability of data related with the probability and impact should be guaranteed to apply the general approach. Hallikas, Virolainen, & Tuominen (2002) analyzed the risk factors in the production network. This research analyzed the risk in the procedure of purchasing and supplying material by categorizing into demand, transportation capacity, finance and price. However, the proposed criteria are subjective and adequate to only production network, not to general supply chain.

Most of prior research related to the SCRM have focused on assessing impact of risk and developing the way to manage the risk. Still, it is hard to find research to consider or evaluate the connected structure of supply chain.

Designing the Supply Chain Structure

Wilding (1998) has proposed a SCRM approach which defines dynamics in supply networks as Supply Chain Complexity Triangle. Also, Choi, Dooley, & Rungtusanatham (2001) has modeled supply networks as Complex Adaptive System (CAS), and Surana, Kumara, Greaves, & Raghavan (2005) has explained how various concepts of systems can be applied to supply network model. Based on the model of CAS, Pathak, Day, Nair, Sawaya, & Kristal (2007) has proved the practical applicability of CAS to model the complicated situation in supply network. In addition, the simulation based approach is the widely accepted in order to analyze and develop the optimal supply chain network structure (W. Kim, 2009; North & Macal, 2007; Pathak et. al., 2007). On the contrary to the simulation, there exists a case which deals with the practical supply chain network (Choi & Hong, 2002;

Jarillo & Stevenson, 1991; Nishiguchi, 1994). Recently, a social network analysis (SAN) has been utilized to analyze the structure of supply chain. It has been already proved the usefulness of SNA for supply chain analysis (Ellram, Tate, & Carter, 2007). Especially, the SNA based approach may be most progressive methodologies in Logistics and SCM (Carter, Ellram, & Tate, 2007). Actually, Borgatti & Li (2009) has insisted that SNA can be applied to analyze the behavioral and systematic mechanism of whole supply chain network. There exists a case which apply SNA approaches to promote the continuous improvement activities of part suppliers in the automobile industry. Also, Y. Kim, Choi, Yan, & Dooley (2011) has applied the concept of centrality to the supply network. Still, some limitations are remained. The insight and contribution of the automobile case is hard to be extended to the general supply chain network. In addition, the impact from the connected nodes is not considered, and they assumed that all nodes have equal weight.

3. DESIGNING EVALUATION METRIC FOR SUPPLY CHAIN VULNERABILITY

The ultimate goal of this research is to analyze the weight that each node has in terms of risk management in order to evaluate the structural vulnerability. To build the quantitative metric to evaluate the weight, the concept of centrality in Graph Theory has been adopted. Following Table 1 shows the notations and their short description for developing quantitative metric.

Risk Propagation Model

As explained in the section 1 and 2, the impact of risk propagates to the other connected node. So to speak, assuming node i (V_i) is connected to the node j (V_j, $a_{ij} = 1$) and the node j is connected to the node k (V_k, $a_{jk} = 1$), the risk of node i can have impact on the node k.

Here, the magnitude of impact can be defined as a function of the type of risk and relationship between V_i and V_j, $f^r(i, j)$. Based on the characteristics of a risk, it is possible to categorize the type of this function as following three different types. First, the impact which the V_j gets is equal to the one that V_i gets from the risk r_1.

$$f^{r_1}(i, j) = I^{r_1}(V_i) \tag{1}$$

In the case of the second type of risk, r_2, the impact of risk in the V_i is divided according to the relative weight that the arc (w_{ij}) has and propagated to the V_j.

$$f^{r_2}(i, j) = \frac{w_{ij}}{\sum_k w_{kj}} I^{r_1}(V_i) \tag{2}$$

The last type of risk, r_3, the impact the V_j receive is dependent to the relationship between V_i and V_j like the distance (d_{ij}). For example, the impact of a risk can be amplified according the distance. On the opposite way, the impact can be diminished as the distance gets further as depicted in the following equation (3).

$$f^{r_3}(i, j) = \frac{1}{d_{ij}} I^{r_3}(V_i) \tag{3}$$

Table 1
Notations and Descriptions

Notation	*Description*
V	Set of vertices
i, j	Index of vertex
V_i	Vertex i ($V_i \in V$)
$A = \{a_{ij}\}$	Adjacency Matrix
$a_{ij} = 1$	If V_i is connected to V_j
R	Type of risk
$I^r(V_i)$	Business Impact of risk type r in V_i
$f^r(i, j)$	Function for risk propagation between V_i and V_j
$C_b(V_i)$	Betweenness centrality of V_i
$C_r(V_i)$	Risk centrality of V_i

Interpreting the Betweenness Centrality

Generally, the centrality is utilized while figuring out the most important node in a network. In other words, the relative importance of each node can be illustrated with the centrality. According to the centrality, each node has different impact on the others (Mizruchi, 1994). The centrality is diversified into the degree centrality, closeness centrality, betweenness centrality, Katz centrality and Eigen-vector centrality according the objectives of network analysis.

In this research, we have devised the quantitative metric to evaluate the structural vulnerability using the betweenness centrality (BC). Different from other centrality metrics, BC of each node is obtained by counting how many times the node is included in the shortest path between any two nodes. Therefore, BC can express the connectivity and reachability among nodes.

$$C_b(V_i) = \sum_{j<k} \frac{g_{jk}(V_i)}{g_{jk}} \tag{4}$$

Here, g_{jk} means the number of possible paths between V_i and V_k, and $g_{jk}(V_i)$ means the shortest path which includes the node V_i.

Nodes which have higher BC value can be regarded as the hub nodes in the network considering the flow of raw material and information. These hub nodes may have impacts on the failure to keep the production plan or defects of products due to the unexpected events in the hub node may be rapidly propagated to the whole supply chain. It makes impossible supply chain to respond to the change of market and to be disrupted (Chopra & Sodhi, 2004).

Designing the Metric for Structural Vulnerability of Supply Chain

By previously explained, the impact from the risk at a certain vertex, V_i, can be classified into two types, directly measured impact and propagated impact from the connected nodes (V_k where $a_{ki} = 1, \forall k \in V$). Therefore, we have to measure the possibility and business impact of risk factors at every node, and also consider the propagated impact based on the connected relationship among nodes.

In this research, the quantitative metric, Risk Centrality (RC), is defined to interpret the risk propagation in terms of network structure as following equation (5).

$$C_r(V_i) = \alpha \sum_k a_{ji} f^r(k,i)\, C_b(V_i) + (1-\alpha)\, I^r(V_i) \tag{5}$$

$C_r(V_i)$ is obtained by summing the propagated impacts from all other connected node as well as the directly measured impact considering the relative weight of each parts. The structural vulnerability of whole supply chain network can be evaluated based on how the risk centrality of each node is distributed. Because the scale of risk centrality each node can be varied according to the number of nodes and the connectivity among nodes, the plat sum, average or variance of risk centrality are not suitable for relative comparison among supply chain networks with different structure.

In this research, the quantitative metric for the structural vulnerability has been devised by evaluating how the risk centrality is concentrated on certain nodes. For example, if a few nodes take most of the risk centrality, it is highly possible the whole supply chain may have great impact when the nodes high risk centrality are disrupted.

$$SV = \frac{\sum_i O(V_i)\, C_r(V_i)}{\sum_k O(V_k)} \quad \text{where,} \quad \begin{array}{l} O(V_i) = 1,\ C_r(V_i) > \mu C_r + \rho\sigma_{C_r} \\ \text{otherwise},\ O(V_i) = 0 \end{array} \tag{6}$$

In the equation (6), the notation $O(V_i)$ means whether the node V_i is outlier or not. In here, we have assumed that the distribution of risk centrality follows the Normal distribution. Thus, the outlier can be statistically determined by assessing how far the risk centrality of the node V_i is located. So to speak, the nodes with abnormally high risk centrality compared with others are determined as the outliers.

4. CASE STUDY: NETWORK STRUCTURE OF CORPORATE M

In this chapter we present the applicability for quantitative metric by applying betweenness centrality to actual networks. Applied network is used by one of the biggest container shipping companies which has more than 600 container ships and 14.7 % in a market share. The purpose of this chapter is to understand how the priorities of nodes are changed based on measurement standard. For this purpose, we first make networks by using the operating routes of corporate M, and we measured in/out-degree, betweenness centrality, and risk centrality individually. In consideration of characteristic of risk propagation, we compare metrics we proposed in this research. Furthermore, we analyze the relationship between port freight volume and risk centrality in order to present the applicability of metrics we proposed in this research.

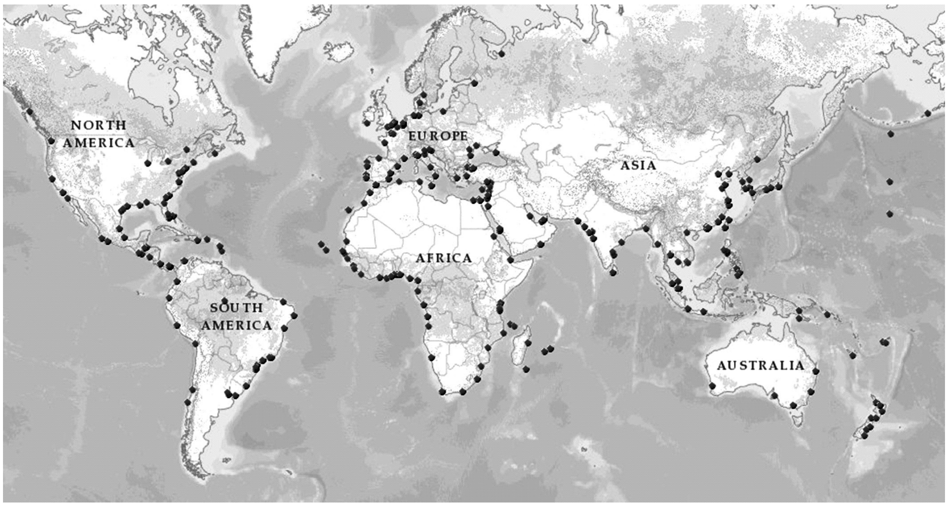

Figure 1: Corporate M's operating ports

Network Status of Corporate M

Corporate M operates 214 routes by the port to 269 ports of call. This M details on the status of the route and port operating as follows Table 2.

When decomposing the respective routes as a single edge, it was composed of 1,739 single edge. Also removing duplicated edges result, it was operating a network of 841 edges.

Network Analysis of Corporate M

For the network analysis, we have measured ports ID-OD without removing duplicated edges. Duplicated edges are part of a different route, but means that the same edges as shown.

Table 2
Corporate M's Operating Routes

Operating route			*The number of routes*
Asia	to	Europe	6
Europe	to	Asia	6
Asia	to	Mediterranean	5
Mediterranean	to	Asia	5
Asia	to	America	9
America	to	Asia	8
Europe	to	America	5
America	to	Europe	4
Mediterranean	to	North America	2
North America	to	Mediterranean	2
		Africa	37
		Central America	27
Europe	to	Middle East	7
Far-east	to	Middle East	10
		Intra-Asia	16
		Intra-Europe	12
		Oceania	21
		South America	32
	Total		214

Table 3
The Result of Port ID-OD

Rank	*Allow duplicated edges*			*Remove duplicated edges*		
	Port	*In-Degree*	*Out-degree*	*Port*	*In-Degree*	*Out-Degree*
1	Shanghai	60	58	Tanjung Pelepas	25	25
2	Tanjung Pelepas	49	49	Algeciras	24	19
3	Ningbo	48	47	Singapore	22	18
4	Singapore	47	49	Hong Kong	14	12
5	Yantian	39	41	Yantian	13	11
6	Algeciras	39	36	Salalah	13	13
7	Busan	37	38	Busan	12	16
8	Bremerhaven	34	36	Tangier	11	10
9	Rotterdam	34	35	Shanghai	11	15
10	Hong Kong	33	35	Jebel Ali	11	11
11	Santos	32	33	Santos	11	12

Rank	*Allow duplicated edges*			*Remove duplicated edges*		
	Port	*In-Degree*	*Out-degree*	*Port*	*In-Degree*	*Out-Degree*
12	Antwerp	29	27	Rotterdam	11	9
13	Manzanillo	26	23	Ningbo	11	8
14	Qingdao	25	27	Antwerp	11	8
15	Chiwan	24	25	Bremerhaven	11	11
16	Balboa	22	24	Valencia	10	7
17	Paranagua	22	21	Manzanillo	10	8
18	Tangier	22	16	Xiamen	9	6
19	Jebel Ali	19	17	Le Havre	9	5
20	Nansha	17	20	Qingdao	8	6

As a result of measuring the ID-OD of the port, Shanghai was the highest and followed by Tanjung Pelepas and Ningbo respectively in allowing duplicated edges. This means that most of the routes operated by M stopped these ports. When remove the duplicated edges, however, there was a change in rank of major ports. Shanghai has been changed to 9th from 1st and Tanjung Pelepas and Algeciras has been changed to 1st from 2nd and 2nd from 6th respectively. This means that Shanghia and Ningbo are used a port of call on many routes, but these ports are origin or destination port of routes in Asia. Otherwise, Tanjung Pelepas and Algeciras are used a port of call on many routes too, but these ports are connected to various other ports.

Table 4
The result of Betweenness Centrality and Risk Centrality

Rank	*Betweenness centrality*		*Risk Centrality*	
	Port	*Value*	*Port*	*Value*
1	Tanjung Pelepas	22355.94	Tanjung Pelepas	56968.57
2	Algeciras	18297.37	Singapore	49138.43
3	Singapore	14846.58	Algeciras	47958.79
4	Said	6362.607	Tangier	44020.63
5	Jebel Ali	6177.268	Felixstowe	41925.58
6	Manzanillo	6086.689	Shanghai	41667.81
7	Balboa	5421.057	Jebel Ali	37852.17
8	Santos	5272.202	Hong Kong	35834.7
9	Busan	5245.313	Colombo	35463.9
10	Salalah	4610.267	Yantian	34678.21
11	Shanghai	4513.348	Kaohsiung	33311.01
12	Tangier	4509.065	Sines	30767.38

Rank	*Betweenness centrality*		*Risk Centrality*	
	Port	*Value*	*Port*	*Value*
13	Auckland	4134.565	Santos	29696.67
14	Bremerhaven	4012.855	Laem Chabang	29010.13
15	Hong Kong	3561.702	Rotterdam	26675.05
16	Newark	3350.274	Xiamen	25938.54
17	Le Havre	3313.561	Jeddah	25825.57
18	Savannah	3281.273	Newark	24076.41
19	Rotterdam	3025.316	Qingdao	22377.21
20	Yantian	3010.293	Chiwan	22024.74

The result of measuring the betweenness centrality and risk centrality, Tanjung Pelepas was measured the highest values of betweenness centrality and risk centrality. And Algeciras and Singapore were ranked 2nd in the betweenness centrality and risk centrality respectively. Actually these ports are hub ports of M but this represents a contrasting result when compared with the global port container volume. In Asia, Shanghai and Singapore are ranked 1st and 2nd respectively in the top 50 global container ports provided by World Shipping Council and Jebel Ali is ranked 9th in Middle East. Rotterdam is ranked 11th port which accounts for the highest global cargo volume in Europe. Especially, although the Tanjung Pelepas was measured the highest value of betweenness centrality and risk centrality in the M's network, it is ranked 20th in the ranking of global container volume. It means that some ports are a difference depending on the global container volume. Actually M operates the hub port by transferring hub port to Tanjung Pelepas from Singapore for handling the container volume in the East Asia. Due to the change of hub port, most routes are via the Tanjung Pelepas instead of Singapore.

In Europe, even though the container volume of Algeciras is less than Rotterdam, betweenness centrality and risk centrality of Algeciras is more than Rotterdam. Since Algeciras is hub port that is connected to the various ports, but the number of duplicated edges is small compared to the other major ports. In contrast, betweenness centrality and risk centrality of Rotterdam was relatively low measured other major hub ports. Since Rotterdam is operated by the origin or destination port of routes like Shanghai. Tangier which another hub port in Europe was ranked 12th in the betweeness centrality ranking but it was quite high ranked 4th in the risk centrality ranking. This means that betweenness centrality measured according to structural characteristic of supply chain network was not reflected the importance of nodes. Otherwise, since risk centrality is calculated according to the betweenness centrality, risk centrality is given a higher weight to the hub nodes. Therefore, the ranking of risk centrality at Tangier is higher than the betweenness centrality.

5. CONCLUSION

In this research, we interpreted the risk propagation model from the network point of view and designed the quantitative metric to evaluate the supply chain vulnerability. The proposed quantitative metric in this research was designed by using the betweenness centrality in graph theory to quantitative level of index such as the importance of each node, the possibility of risk occurrence from the certain node and the impact of the risk incurred. In order to demonstrate the applicability of vulnerability evaluation metric, we carried out the case study by using the actual network. Thought the experiment, we could identify the Corporate M's hub ports and the values of betweenness centrality and risk centrality are high measured from the hub ports. It means that the risk is converged on the hub ports and then it is propagated to another node.

By using the proposed metric, it could be utilized the supply chain design, supplier selection and location selection and so on. For example, in case of supplier selection, we can predict the effect of propagated risk by assessing the supply chain of supplier. And also, in supply chain design phase, we could distribute the risk properly using our metric.

However, in proposed metric, we do not consider the reverse flow and the characters of supply chain. Thus it cannot apply the collecting and returning products. Therefore, we need to develop the metric which is applied collecting and returning products and consider the characters of environment of industry and locality in the future. In addition, in order to apply the characters of supply chain network, we need to conduct the sensitivity analysis to determine the risk centrality distribution in accordance with changing the values of α and ρ.

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