Ph.D. Dissertation of Business Administration

An integrated model for supply network resilience: capabilities, exchange relationship, and network attributes

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ABSTRACT

The supply chain management (SCM) activities and its performance become vulnerable due to sudden disruptive events in the business process. Specifically, among three phases (sense, respond, recover) supply chain (SC) experience under disruption, we are interested in post-event recovery activities. For example, after the supply disruption, firms must transfer equipment and switch production to alternative or new suppliers utilizing network capability and flexibility. Such recovery activities are termed as resilience activities or a term, SC resilience. The primary objective of this thesis is to thoroughly investigate all the important attributes related to SC resilience, and to propose a comprehensive scheme to show the level of resilience among multiple firms from a network perspective. This thesis considers three problems in a sequential manner so that the critical issues fostering SC resilience can be practically resolved: (1) to determine the critical attributes for SC resilience; (2) to present a network-based structure for managing the levels of resilience; and (3) to propose comprehensive network resilience model for both deterministic and probabilistic situations.

This thesis first elicits important resilience attributes, among which a number of determinant attributes are critical for supply chain sustainability. The resilience capabilities introduced in the existing literature are systematically investigated and classified, based on a value hierarchy. A survey study is then conducted in order to validate the important exchange relationship attributes and supply chain capabilities. Second, a graphical representation is proposed to visualize the resilience relationship in a network formation. A node here represents a partner firm's resilience capability in the supply network and the network value consists of the positional value of the firm. We then adopt an outranking methodology, concordance discordance approach, to provide a process to identify the improvement priority order. Finally, a total network resilience model is proposed to handle resilience levels and interrelationships of the firms simultaneously. The proposed model is also extended to serve as a probabilistic model, along with a number of sensitivity studies, to improve its applicability.

The study may contribute theoretically to the literature as follows: First, this thesis isolated four key determinant attributes of supply chain resilience through a comprehensive analysis of existing capabilities. The impact of the four attributes on resilience has been verified with a survey study. Second, the interrelationships of the firms have been expressed using leader-member exchange theory. Through the survey analysis, it was found that leader member exchange affects supply chain resilience significantly. Third, a bicriterion network resilience model using resilience and network value has been proposed, along with an ordering approach. The network representation visualizes not only all the levels of resilience of the firms but also their influences within the network structure. Fourth, a total network resilience (TNR) model is developed, through which one can handle both resilience and interrelations among the firms. The model is applicable to both deterministic and probabilistic cases.

Investigating the impact of supply chain capabilities, exchange relationship, and network attributes on supply network resilience offers a fertile avenue for future research. From supply chain perspective, it is recommended that future studies explore the causal relationships among SC capabilities and SC resilience based on different phases of a disruption (i.e., pre-, during-, and post-disruption). One can also investigate the relational behavior based on divergence or crossvergence contexts for more comprehensive analysis. Another possible research direction is to utilize our proposed TNR model in considering triadic relationship and diverse network structural properties. With a further effort on elaboration, we believe that the research results may prove to be a solid basis for network based research in the area of supply chain management.

Keywords : Supply chain management, SC resilience, SC capabilities, SC exchange relationship, supply network, supply network resilience

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CHAPTER 1

INTRODUCTION

1.1 General background

Supply chain management (SCM) has become a vital issue for most organizations as the constant advancements in technology compel firms to consider an effective use of collaborative structure for many business functions. Not only does the SCM fulfill the function of supply and demand of parts and materials in the stages of procurement and distribution, but it also helps the supply chain (SC) members to maintain formal relationships with other business units, such as research and development, human resources, intellectual property rights, and business strategy. Moreover, with a partnership built on the basis of an extended supply network, the firms are also able to enhance their competitive advantages for future business opportunities.

Several studies have analyzed the impact of SCM partnerships on various operational issues. They emphasize both the positive and negative aspects of the collaboration, depending on the type of the relationship. Yan and Dooley (2014) and Bellamy et al. (2014) have shown that the partnership makes possible high-quality design and innovation activities, while Ivanov et al. (2014) and Li et al. (2015) point out the risks associated with it. These research outcomes indicate that the benefits of SC collaborative activities come at a great cost, and that the role of capabilities and its appropriate balance need to be investigated in the future for a sustainable SC outcome.

As SCM become complicated with an increase in the uncertainty associated with information flow and decision behaviors, a number of researchers have recently brought up the issues of resilience of SC. Their main concerns are related to maintaining sustainable competitiveness of the SCM partnerships in the face of uncertain operational situations brought about by disruptive events (Fahimnia & Jabbarzadeh, 2016; Kim, Chen, & Linderman, 2015; Klibi, Martel, & Guitouni, 2010; Lewis, Brandon-Jones, Slack, & Howard, 2010). Although they all focus on the importance of resilience in the real world, they fail to identify a set of determinants or attributes that can lead to the designing of an SCM resilience strategy.

A set of key attributes that foster resilience has been identified (Ambulkar, Blackhurst, & Grawe, 2015; Hohenstein, Feisel, Hartmann, & Giunipero, 2015; X. Li, Wu, Holsapple, & Goldsby, 2017; T.J. Pettit, Croxton, & Fiksel, 2013; L. Purvis, Spall, Naim, & Spiegler, 2016; Scholten & Schilder, 2015), but it does not cover the dynamic business issues of interest that surround the firms. Despite the existence of various studies that measure SC resilience (Brandon-Jones, Squire, Autry, & Petersen, 2014; V.L.M. Spiegler, Potter, Naim, & Towill, 2016; Tukamuhabwa, Stevenson, Busby, & Zorzini, 2015; Vugrin, Warren, Ehlen, & Camphouse, 2010), a comprehensive model which incorporates and analyzes all the critical resilience attributes remains unaddressed.

From the literature review, it has been observed that a comprehensive model is needed for SC resilience. The newly updated SC resilience focused model must incorporate the following three aspects: (i) notable SC capabilities that determine the level of resilience; (ii) observable measurement constructs for the capabilities; and (iii) a network-based representation for strategic decision making. By resolving the three aspects of resilience, one can not only isolate the valuable capabilities that are specifically related to SC resilience but also proactively protect the SCM partners from being vulnerable due to uncertainties.

This thesis is unique in that it proposes a total network resilience model for SC resilience management based on the interrelationship among firms. Resilience here is viewed as an integrated variable that is observable from various perspectives, according to the nature of the dynamic relationship among the stakeholders. The originality of this thesis is its focus on developing a comprehensive network model that can represent the resilience level, network structure, and interrelationship between the firms in each pair. With the proposed model, one can compute the level of resilience of the SC and design a strategy for balanced resilience in case of expected disruptive events. The reproducibility of this thesis is proved by three different approaches: First, both a thorough literature review and a survey study are used for determining key resilience capabilities. Second, network theory is employed in computing the resilience potential of each firm. Third, a total network representation, which includes the firms' interrelationship, is proposed. A multi-criteria decision-making methodology (concordance and discordance approach) is used as the key methodology as its benefit includes identifying the firms' ratings based on their probabilistic coalitions. This thesis offers three major practical contributions: (i) it contributes to the existing SC literature by proposing a comprehensive network model for SC resilience, (ii) it shows how to utilize the proposed model in diverse situations, and (iii) it helps the practitioners to observe the outcome of the model based on a real world case study.

1.2 Research objectives

The primary objective of this thesis is to thoroughly investigate all the important attributes related to resilience, and to propose a comprehensive scheme to show the level of resilience among multiple firms from a network perspective. The research outcomes of this thesis may contribute toward defining the key resilience attributes for theoretical researchers and provide a practical tool to maintain a balanced structure of resilience for the practitioners.

This thesis makes an effort to develop a graphical representation system for analyzing the level of resilience—taking the case of multiple firms connected in a network (also known as supply network)—in three approaches. It first elicits important resilience attributes, among which a number of elements are critical to SCM sustainability. The resilience capabilities introduced in the existing literature are systematically investigated and classified, based on a value hierarchy. A survey study is then conducted in order to validate the important exchange relationship attribute and SC capabilities that are important in assessing resilience. Second, a graphical representation is then proposed in such a way that the resilience relationship can be visualized within a network formation. Here, we transform the node and place valuation model, which was originally utilized in the transportation studies, to a node and network value model for the application in SCM. A node here represents a connected firm's resilience capability in the supply network and the network value consists of the positional value of the firm. We then adopt outranking methodology to provide scientific means to identifying improvement priority order. Finally, a comprehensive graphical representation system is proposed for visualizing the comprehensive firm's values including, resilience, network value, and relationship-based value of the firms. The model is also considered as a probabilistic model along with a number of sensitivity studies to improve the applicability of the proposed model.

This thesis consists of the following six chapters:

In Chapter 2, The definition of resilience is explained and the problems of interest are stated. The existing research studies in the areas of SC resilience, network resilience models, and relationship-based decision systems are investigated. Terminologies, assumptions, and notations are also included here.

In Chapter 3, the important resilience elements are identified from the existing literature. The elements are then reduced to a set of resilience capabilities via a systematic analysis regarding their hierarchical relationships. Here, the Leader Member Exchange (LMX) model is employed to identify the impact of intermediary factors on maintaining SC resilience.

In Chapter 4, a bicriterion network relationship is proposed to compute and visualize both the firm- and network-based resilience value. An outranking methodology, the concordance and discordance approach, is employed to determine improvement priorities of the firms to achieve the high level of overall network resilience. A case in the area of electronic industry is examined here to show the applicability of the proposed system.

In Chapter 5, a comprehensive network resilience evaluation model, called the total network resilience model, is proposed by incorporating the LMX levels among the firms within a network system. The ordering approach is extended to set priorities of the firms considering their resilience and strength of interrelationships simultaneously. A probabilistic model is also proposed for generalizing the model and a number of sensitivity studies are also included for validation of the model.

This thesis is concluded in the sixth chapter along with research limitations and future research task.

CHAPTER 2

PROBLEM STATEMENTS AND LITERATURE REVIEW

2.1 Problem statement

The problem under consideration in this thesis deals with the case when the SCM activities and its performance become vulnerable due to sudden disruptive events in the business process. Specifically, among three phases (sense, respond, recover) SC experience under disruption, we are interested in post-event recovery activities. For example, after the supply disruption, firms must transfer equipment and switch production to alternative or new suppliers utilizing network capability and flexibility. The total recovery activities are termed as resilience activities or a term, SC resilience. SC resilience has been introduced in the literature to emphasize to the practitioners the need for preparation for recovery and improvement from any risk of uncertain disruptions. This thesis considers three problems in a sequential manner so that the critical issues fostering SC resilience can be practically resolved.

- PROBLEM 1: What are the key SC capabilities and exchange relationship values that enhance SC resilience performance? A comprehensive set of resilience attributes is yet to be determined based on the measurement scales conformed by the real world practitioners.
- PROBLEM 2: How can we visually present the level of supply chain resilience to aid the practitioners in making integrative decisions in supply network management? Some researchers suggested graph theory driven network analysis for resolving this problem but lacked practical suggestion under the considering of multiple measures of networks. The existing studies are limited to the network-level performance and do not consider the individual firms' resilience level and the network value simultaneously. We, therefore, are in dire needs of a network representation based on the network structure for evaluating the resilience potential for each firm.
- PROBLEM 3: How can we offer a holistic view of SC resilience based on the interrelationships among the firms, and provide a decision aid for

sustaining business environments? The existing studies assume that the relationships among the firms within a SC are often collaborative with high relationship quality. However, the relationships among business firms are competitive and vary according to their respective management strategies. This aspect of SC resilience has not been studied thus far.

2.2 Literature review

Three streams of literature backgrounds exist: (1) SC capabilities driven SC resilience management, (2) network perspective integrated SC resilience management, and (3) comprehensive network resilience view based on exchange relationship. Readers are referred to the literature review section of each chapter for a more in-depth review.

2.2.1 SC capabilities driven SC resilience management

The role of resilience has become vital because today's SC system is expected to perform well, with or without disruptions. While the definitions of resilience vary according to the contexts (i.e., physical, ecological, socio-ecological, psychology, disaster management, organizational, and engineering) (Jüttner & Maklan, 2011), resilience in SCM context is defined as "the ability of a firm to cope with the consequences of unavoidable events in order to return to its original operations or move to a new, more desirable state after being disturbed (Christopher & Peck, 2004; Jüttner & Maklan, 2011). While resilience capabilities may appear as preemptive measures against disruptive events, they can also be regarded as the means to gain competitive advantage over competitors. For example, not all firms are able to react and recover quickly from the negative consequence of disruptions (Hendricks & Singhal, 2005).

Based on resource-based theory, SC capabilities play critical roles in empowering overall resilience performance. Consequently, existing empirical studies of SC capabilities in resilience contexts have proliferated. Jüttner and Maklan (2011) found that risk management strategies significantly affect the levels of SC members' vulnerability (i.e., revenue, cost, and lead time/agility) and resilience (i.e., flexibility, velocity, visibility, collaboration). Moreover, Bhamra et al. (2011) stated that small and medium enterprises can achieve resilience by adapting to risks based on their existing capabilities and resource availability. Based on a systematic review of 67 peer-reviewed articles from 2003 and 2013, Hohenstein et al. (2015) identified 36 SC resilience elements. Among those 36 elements, flexibility, redundancy, collaboration, visibility, agility, and multiple sourcing were the top six in terms of the number of appearances in various studies. From these studies, we can conclude that the applicability of SC resilience measures has not been as clearly investigated as the conceptual and empirical examination of SC resilience. There has been a lack of guidance for both researchers and practitioners in understanding the interrelationship among SC capabilities and their impact on resiliency.

Most importantly, resilience is viewed as a dynamic process that depends on the life context from psychology perspective (Ponomarov & Holcomb, 2009). Reich (2006) described human resilience as "a capacity to recover and even to enhance individual adaptive capacities" under adversity, and found that the central principles of resilience (control, coherence, and connectedness) could result in effective management.

2.2.2 Network perspective integrated SC resilience management

Modern supply chain management (hereafter referred to as supply network or SN) has recently gained attention in theory and practice for its level of exposure to vulnerabilities. In particular, for supply networks that involve numerous overseas-based firms, every member in the network are largely exposed to hazards, strategic, financial, operational, infrastructural, and demand and supply vulnerabilities (Chowdhury & Quaddus, 2015). While the speed of globalization (i.e., outsourcing R&D, sourcing from countries with lower) may be responsible for creating leaner SC setting, comes at a great cost of being too fragile to deal with disruptions (Christopher & Peck, 2004; Hendricks & Singhal, 2005; Wagner & Bode, 2006). Globalization creates supply network relationship with elongated chains, which requires a high level of coordination to control for increased levels of uncertainty in inventory management (Greening & Rutherford, 2011). As part of the effort to deal with variety and levels of uncertainties, many studies have investigated and developed necessary capabilities that supply networks must acquire to remain resilient.

Existing studies on SC resilience often vary in terms of their points of view due to the growing interest in the different phases of experience in case of disruptive events. The pre-disruption phase and the ongoing phase of disruption involves the ability to absorb shocks and adapt as a network, as a whole rather than individually. Sheffi and Rice Jr. (2005) identified two important variables that define firm's resilience performance: market positioning (the level of market power) and SC responsiveness (low or high). The post-disruption phase often addresses the ability of a network to return to its original pre-disruption state or move to a better state. Scholten and Schilder (2015) discovered that the positive impact of collaborative activities applies beyond the dyadic level, and it creates resiliency at the network level. Specifically, high level of collaboration is claimed to increase flexibility, velocity, and visibility.

The structural relationship of supply networks has greater implications than a simple business connectivity representation. Based on the social network theory, firms can gain social capital through interaction among interconnected network relationships (Gao, Xie, & Zhou, 2015). Network analysis not only helps visualize the complexity of overall partnership, but also provides visual support for the decision makers in preparing for supply network disruptions. For example, Basole and Bellamy (2014) created a visual decision support system for complex risk management and provided examples on how to systematically identify the level of global supply risk of a three-tier supply network. Bellamy et al. (2014) empirically demonstrated that (i) network accessibility positively drives innovation output; (ii) network interconnectedness moderates the accessibility-innovation relationship; and (iii) firm's absorptive capacity strengthens the effects of structural relationships on innovation output. Most recently, Kim et al. (2015) identified how supply network structures influence disruptions, and the means to evaluate supply network resilience level using graph theory. Assuming every firm (node) and its connection (link) has an equal probability of failure, they propositioned that network resilience is determined by the degree distribution. Thus, network structural design and its properties can shed light on resilience management of complex network from both theoretical and managerial perspective.

2.2.3 Exchange relationship based comprehensive network resilience view

A supply network (SN) may behave and operate based on the types of contracts made among the firms, but SN resilience is bound to be affected by the social relationship formed among the parties. The Leader-Member exchange (LMX) theory describes that the success of leadership is achieved when both the leader and followers develop a mature partnership enabling various benefits (Graen & Uhl-Bien, 1995). Though LMX was originally introduced into the literature for the area of organizational behavior management, the concept (knowingly or unknowingly) has been lately employed in SN context. Three notable extension logics are as follows: First, LMX infers SN member's perceived maturity of partnership with the SC leader. Second, suppliers with a high level of LMX may have share higher norms and values with the SC leader. Third, suppliers with a high level of LMX may depict a stronger desire to aid and support SC leader in case of disruptive events.

A SC can be viewed as a single conglomerate, where each participating firm is viewed as a member of a conglomerate rather than a separate entity (McAdam & McCormack, 2001). Consequently, the top managers in SN are advised to measure and manage performances of all the firms participating in a SN, rather than the performance of individual firms (Robinson & Malhotra, 2005). Every SN must have one or more representative leading firms, who are expected to demonstrate an effective SN leadership, described as “a significant impetus for directing and managing while achieving impactful SCM performance” (Sharif & Irani, 2012). As an extension to the leadership theory, LMX measurements have been developed based on three aspects: respect, trust, and obligation. SC studies can benefit from integrating this theoretical perspective in identifying the impact of different types of exchange relationship on SN performance. SN leader is defined as an “instinctive” leader with financial power and/or exceptional knowledge of final products and services who is responsible for coordinating and overseeing the whole supply chain (Melnyk, Lummus, Vokurka, Burns, & Sandor, 2009). It is quite usual to interpret leadership not just only for the group of individuals but also for representing interrelationships among organizations.

The investigation of types of relationships and its effectiveness in building SC competitive advantage has been viewed in many aspects over the time. Initially, Hult, Ketchen, & Nichols (2002) found that "cultural competency" including learning within SC effectively reduces cycle time. Moreover, Malhotra, Gosain, & Sawy (2007) established that firm's adaptation to its environment can be improved by the external knowledge. Such firms' characteristics and activities that enhance SC competitive advantage started becoming specific. Thus, we integrate LMX for SC resilience and develop total network resilience model. To the best of our knowledge, this is study is one of the first to contribute in the SC literature by refining SLMX and incorporating it into a network resilience model for the first time.

2.3 Research assumptions, terminologies, and notations

2.3.1 Assumptions

The following assumptions are made in this thesis:

First, a SC has been given as a fixed structure. A fixed model is considered here so that the relationships among the firms are predetermined. The network representation reviewed in this study is the ego-centric network, which includes only firm and link information relevant to the focal or leading firm in the supply network of interest. Thus, we exclude suppliers that do not directly or indirectly contribute to final service or product at the focal firm level.

Second, each SC member is able to provide and indicate the levels of resilience-focused capabilities related to the connected firms. The attributes may be either ordinal or cardinal, or both, in their measurement styles. This is important as, realistically, some firms may not want to disclose the actual level of their firm's status. Thus, we assume that firms will be able to share ordinal evaluations at the least.

Third, the interrelationships between a pair of firms in a SC can be specified. The relationships among business firms are often competitive and vary according to leadership exchange strategies. This aspect of SC resilience can be represented as a form of the Leader Member Exchange (LMX) theory which has been used in organizational development.

Fourth, any LMX level between two firms can be assessed as the probability that two firms maintain normal relationship at a disruptive event. It is noted that we use SLMX (Supply chain LMX) later in this study to distinguish from LMX.

2.3.2 Terminologies

For clarity of this study, the key terminologies are defined as follows:

Supply network: Modern supply network model composed of SC members (visually represented as nodes) that directly and indirectly supplies, delivers, or contributes (visually represented as links) to the final products and services for usage by end customer.

Supply chain leadership: Ability to create trust, respect, and mutual obligation that influences the supplier-buyer relationship between parties.

Supply chain leader: An "instinctive" leader with financial power and/or exceptional knowledge of final products and services who is responsible for coordinating and overseeing the whole supply chain (Melnyk et al., 2009).

Supply chain member: Anyone who is involved in a supplier-buyer relationship but not a leader.

Total network model: A network model that provides all the information for both nodes and links (or arcs and branches).

Total network resilience model: A network model that provides all the information regarding supply chain resilience for both nodes and links.

Enhancer: An element that emphasizes the concept of causal relationships (typically expected to lead to a certain performance or outcome).

Antecedent: An alternative term for an enhancer.

Focal firm: The key buying firm, supply chain leader, among the firms of supply chain.

Capability: A comprehensive metric that represents a firm's level to achieve superior performance and sustained competitive advantage over competitors.

Competency: A term that is often used for stating one's capability.

Element: An ordinary expression for an attribute or criterion.

Attribute: A sub-criterion that measures capability or competency.

Important attribute: An attribute that has higher priorities among attributes.

Determinant attribute: An attribute that is critical to SCM sustainability.

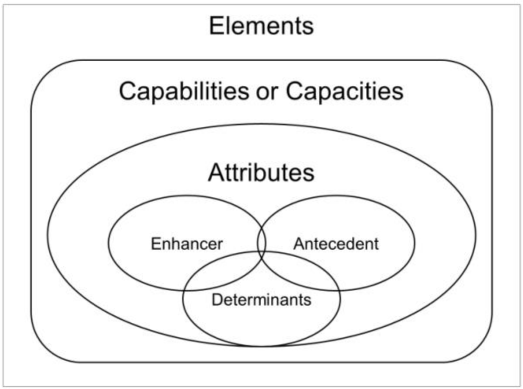


Figure X1. Terminologies map

2.3.3 Mathematical notations

The following notation is related to network resilience studies that are used in this research:

Notation	Description	
N	Set of nodes in supply network	$Let\ n \in N$
Q	Set of edges in supply network	$Let\ q \in Q$
C	Set of attributes of firm's value (C=R+T)	$Let\ c \in C$
R	Set of SC resilience capabilities	$Let\ r \in R$
T	Set of supply network attributes	$Let\ t \in T$
μ_{ir}	Level of resilience capability of node i	$where\ i \in N, r \in R$
γ_{it}	Set of network attribute of node i	$where\ i \in N, t \in T$
$\tau(i,j)$	Level of SCLMX between node i and node j	$where\ i, j \in N$
k_{ic}	Weight of node i's value attribute c	$where\ c \in C$ $where\ c = 1,..\ r+t$
k_{ir}	Weight of node i's resilience capabilities r	$where\ r \in R$
$w(i,j)$	Transactional weight between node i and node j	$where\ i, j \in N$
$I(i)$	Inferiority count of node i	$where\ i \in N$
$S(i)$	Superiority count of node i	$where\ i \in N$
$\pi(i)$	Importance weight of concordance (+) or discordance (-) of node i	$where\ i \in N$
$\chi(i)$	Weighted level of concordance (+) and discordance (-) of node i	$where\ i \in N$
$P\ (n_i)$	Survival likelihood of node i	
$Pr(\mu_{ir} \leq \varphi_{ir})$	Survival likelihood of node i in case of disruptive event in which node's resilience attribute μ has the value of φ	$where\ i \in N$

CHAPTER 3

EXCHANGE RELATIONSHIP, SC CAPABILITIES AND RESILIENCE

This chapter determines key supply chain (SC) capabilities that lead to SC resilience. The existing studies are structurally investigated to identify a set of capabilities of resilience. As an effort to build a comprehensive model based on a repository of information provided by existing studies, a survey study is then conducted to decide critical factors that affect SC resilience performance.

3.1 Theoretical background and conceptual model

3.1.1 SC resilience and competitive advantage

While traditional supply chain management (SCM) has put a great emphasis on lean management for an effective and efficient performance, the modern SC is different. In recent years, the nature of SC has transitioned from a linear relationship to a complex network relationship as SCs no longer represent linear chains or processes (Christopher & Peck, 2004). Accordingly, the role of resilience has become vital because today's SC system is expected to perform well, with or without disruptions.

Haimes (2006) summarized the dual aim of resilience approaches against disruptions as follows: (1) to recover to the desired state within acceptable time and costs and (2) to minimize the effectiveness level of risk. However, with an increase in the complexity of the supply network, the cumulative risk level contributed by the participating members of the supply network has worsened considerably. Moreover, the frequency of disruptions and level of risk exposure are mostly environmental driven and, are therefore, uncontrollable from a firm's perspective. Thus, due to the nature of the issue, many researchers have focused on the formal objective. While the definitions of resilience vary according to the contexts (i.e., physical, ecological, socio-ecological, psychology, disaster management, organizational, and engineering) (Jüttner & Maklan, 2011), resilience in SCM context is defined as “the ability of a firm to cope with the consequences of unavoidable events in order to return to its original operations or move to a new, more desirable state after being disturbed (Christopher & Peck, 2004; Jüttner & Maklan, 2011).

The operationalization of the resilience approach has faced lack of unanimity until the recent study of Ambulkar et al. (2015). Several studies pointed that that the definitions of resilience in SCM context have been ambiguous (i.e., Ambulkar et al., 2015; Bhamra et al., 2011; Hohenstein et al., 2015; Ponomarov and Holcomb, 2009). Thus, Ambulkar et al. (2015) developed and validated resilience with four measurement variables (ability to cope with disruptions, ability to adapt to disruption, ability to quickly respond to disruption, and ability to maintain high situational awareness).

While resilience capabilities may appear as preemptive measures against disruptive events, they can also be regarded as the means to gain competitive advantage over competitors. For example, not all firms are able to react and recover quickly from the negative consequence of disruptions (Hendricks & Singhal, 2005). Thus, based on the assumption that firms are continuously exposed to a similar level of potential threats, firms with internal and external capabilities to adopt and recover faster than competitors can create sustainable competitive advantage (Christopher & Peck, 2004; Hohenstein et al., 2015; Jüttner & Maklan, 2011; T.J. Pettit et al., 2013; Ponomarov & Holcomb, 2009; Rice Jr & Caniato, 2003). The benefits of the resilience practice are illustrated in **Figure A1.**

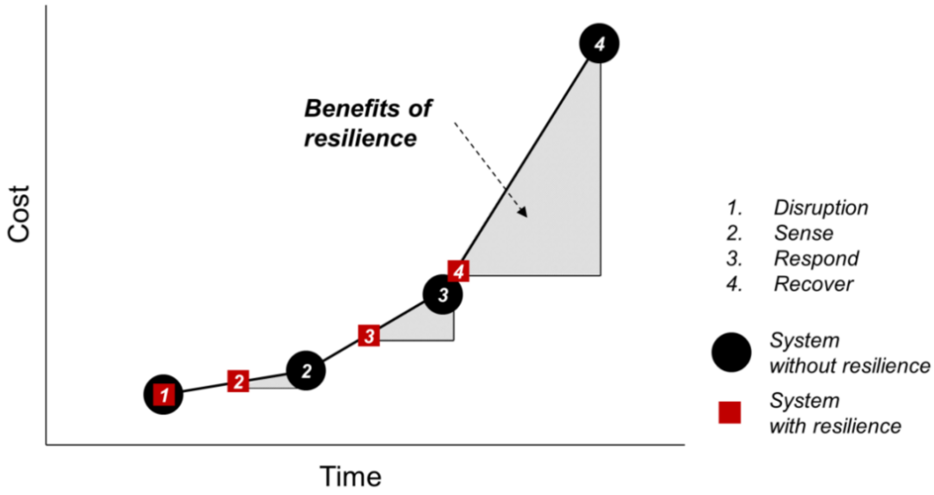


Figure A1. Benefits of resilience adopted from Purvis et al. (2016)

3.1.2 SC capabilities related to SC resilience

Existing capabilities are an essential asset in preparing for both potential business threats and opportunities, and there is an extensive literature identifying key capabilities that enhance SC resilience. Notably, Pettit et al. (2010) developed the SC resilience framework based on the following seven categories of vulnerabilities: turbulence, deliberate threats, external pressure, resource limits, sensitivity, connectivity, and supplier-customer disruptions. And they also stated that such vulnerabilities should be managed by management controls that ultimately result in SC capabilities: flexibility in sourcing, flexibility in order fulfillment, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, organization, market position, security, and financial strength. Pettit et al. (2013) concluded their study by proposing a measurement tool called Supply Chain Resilience Assessment and Management, emphasizing the need for a balance between vulnerability and capabilities in order to manage effectively and better than competitors.

Empirical studies of SC capabilities in resilience contexts have also proliferated. Jüttner and Maklan (2011) found that risk management strategies significantly affect the levels of SC members' vulnerability (i.e., revenue, cost, and lead time/agility) and resilience (i.e., flexibility, velocity, visibility, collaboration). Moreover, Bhamra et al. (2011) stated that small and medium enterprises can achieve resilience by adapting to risks based on their existing capabilities and resource availability. Based on a systematic review of 67 peer-reviewed articles from 2003 and 2013, Hohenstein et al. (2015) identified 36 SC resilience elements. Among those 36 elements, flexibility, redundancy, collaboration, visibility, agility, and multiple sourcing were the top six in terms of the number of appearances in various studies.

From these studies, we can conclude that the applicability of SC resilience measures has not been as clearly investigated as the conceptual and empirical examination of SC resilience. There has been a lack of guidance for both researchers and practitioners in understanding the interrelationship among SC capabilities and their impact on resiliency. **Table A1** summarizes the current state of knowledge about resilience capabilities and overlapping terminologies (relevant indicators are noted in bold texts).

Table A1. 15 key SC capabilities related to resilience

Capabilities	Descriptions
Flexibility	*The ease with which a supply chain can change its range number (i.e. the number of possible "options") and range heterogeneity (i.e. the degree of difference between the "options") in order to cope with a range of market changes/events while performing comparably well* (Jüttner & Maklan, 2011) **Redundancy, backup suppliers, easy supplier switching, distribution channels, flexible production systems, volume flexibility, multi-skilled workforces**
Redundancy	*Ability to respond to sudden changes through multiple suppliers and slack resources in production or transport capacity* (Hohenstein et al., 2015) **Flexibility, production slack, transportation capacities, multiple sourcing and production/supplier locations**
Velocity	*The speed with which a supply chain can react to market changes and events* (Jüttner & Maklan, 2011) **Response efficiency, recovery efficiency, elapsed time**
Visibility	*The extent to which supply chain actors have access to, or timely share information about supply chain operations, other actors and management which they consider as being key or useful to their operations* (Jüttner & Maklan, 2011) **Early warning, communication, information sharing, real-time monitoring**
Collaboration	*The level of joint decision making and working together at a tactical, operational or strategic level between two or more supply chain members. Scalable through the magnitude of relationship strength, quality and closeness* (Scholten & Schilder, 2015) **Information sharing, goal congruence, decision synchronization, coordination, cooperating, joint-decision making, knowledge sharing, supplier certification, supplier development**
Agility	*The ability to reconfigure supply chain resources to respond to sudden changes in supply/demand* (X. Li et al., 2017) **Responsiveness, flexibility, communication, information sharing, visibility, quick SC redesign, velocity**
Robustness	*The ability of a supply chain to resist change without adapting its initial stable configuration* (L. Purvis et al., 2016) **Buffer capacity, inventory redundancy**
Efficiency	*The capability to produce outputs with minimum resource requirements* (T.J. Pettit et al., 2013) **Leanness, efficiency, cost efficiency**

Table A1. 15 key SC capabilities related to resilience (cont.)

Capabilities	Descriptions
Alertness	*The capability of a supply chain to detect changes, either x or from the internal supply chain network, in a timely manner (Li et al. 2017)* **Situational awareness, risk awareness, anticipation, contingency plans, communication protocols**
Information sharing	*The degrees of communication, trust, and interdependence for their willingness to work together in a joint manner (Wu et al. 2014)* **Knowledge**
Operational Competency	*The integrated environment that provides end-to-end interaction of orders, inventory, transportation and distribution to facilitate supply chain* (Ponomarov & Holcomb, 2009) **Strategic response, operational alertness/ response, episodic alertness/response , Integration, operational capabilities, transparency, reengineering**
Technological capability	*The incorporated advanced product and process technologies that enable suppliers to be resilient enough to adjust with technological turbulence* (Rajesh & Ravi, 2015b) **Access to keystone vulnerabilities, technological tool**
Alignment	*The process of co-developing systems to evaluate and publicize each other's performance, sharing costs, risks, and benefits among supply chain partners* (Scholten & Schilder, 2015) **Incentive alignment, inter-organizational alignment**
Cultural Competency	*The capacity to be sensitive toward the surrounding economic, environmental and societal and changes, especially changes in customer values and behavior and the ability to transfer this knowledge into meaningful business practices* (Eltantawy, 2016) **Cultural competency, continuity management, organizational culture**

3.1.3 Leader-Member exchange theory based SC management

A SC may behave and operate based on the types of contracts made among the firms, but SC resilience is bound to be affected by the social relationship formed among the parties. Resilience is viewed as a dynamic process that depends on the life context from psychology perspective (Ponomarov & Holcomb, 2009). Reich (2006) described human resilience as "a capacity to recover and even to enhance individual adaptive capacities" under adversity, and found that the central principles of resilience (control, coherence, and connectedness) could result in effective management. As Ponomarov and Holcomb (2009) noted, resiliency is achieved by a community rather than individuals; thus, this idea can be applied to the SC domain as well.

A SC can be viewed as a single conglomerate, where each participating firm is viewed as a member of a conglomerate rather than a separate entity (McAdam & McCormack, 2001). Consequently, the top managers in SC are advised to measure and manage performances of all the firms participating in a SC, rather than the performance of individual firms (Robinson & Malhotra, 2005). Every SC must have one or more representative leading firms, who are expected to demonstrate an effective SC leadership, described as "a significant impetus for directing and managing while achieving impactful SCM performance" (Sharif & Irani, 2012).

In leadership studies, a theoretical perspective of leader and follower relationship has been formalized as "effective leadership process occurs when leaders and followers are able to develop mature leadership relationships (partnerships), and thus, gain access to the many benefits of these relationships" (Graen & Uhl-Bien, 1995). As an extension to this theory, LMX measurements have been developed based on three aspects: respect, trust, and obligation. SC studies can benefit from integrating this theoretical perspective in identifying the impact of different types of exchange relationship on SC performance.

Till now, several studies have operationalized SC leadership and validated its effectiveness on financial outcome and customer satisfaction (i.e., Kuei et al., 2001; Ou et al., 2010). However, its role in the SC resilience performance remains to be analyzed; thus, a hypothetical model to fill this knowledge gap is proposed in **Figure A2**.

HYPOTHESIS 1 There is a positive relationship between the level of Leader-Member exchange relationship and the level of SC capabilities

HYOPTHESIS 2 There is a positive relationship between SC capabilities and SC resilience in the post-disruption context

Figure A2. Conceptual framework of exchange relationship theory based on LMX-SCRES model

3.2 Research design and methodologies

Prior to developing a hypothetical model of the abovementioned conceptual framework, we have taken the following steps to delineate a common set of resilience capability measurements defined in 53 studies. Thus, we first proceeded with interpretive structural modeling (ISM) as a semi-quantitative approach for identifying key SC resilience capabilities based on existing studies. Then we used structural equation modeling to understand the moderating role of exchange relationship on resilience performance.

STUDY 1 Identification of key SC resilience capabilities using interpretive structural model analysis

STUDY 2 Analysis of LMX-SCRES using structural equation model analysis

3.2.1 Study 1 – Interpretive structural modeling

Here we identify all the key elements that are important for the resilience of the SC and reduce them to generate a group of critical elements for SC resilience. As mentioned in the previous section, the critical capabilities must represent the essence of resilience. We first examine the existing literature for selecting all the elements related to SC resilience. Then, an interpretive structural model is constructed to extract key SC capabilities required for achieving resilience performance. The key capabilities are then examined in terms of measurability so that they can be incorporated in the hypothesized model as objective measures.

ISM is initially created to configure an order sequence of contextual relationships or elements, and to assist decision makers in understanding complex system thereby creating action plans accordingly (Malone, 1975).

ISM methodology has been found to be effective in two different research objectives. First, as an identification of order and direction among complex process system, Wu et al. (2015) clarified and established levels of problem structures and factor priorities with related to operational flow of offshore pipeline project. Faisal et al. (2007) identified 6 levels of information risk mitigation process in a supply chain and analyzed them based on four different categories (autonomous, dependent, linkage, and independent enablers). Second, as means to delineate critical practices or elements that superiorly determines others, Govindan et al. (2015) identified critical lean, green, resilient practices which top managements should focus to improve SC performance in automotive context. Diabat et al. (2012) defined five types of risks involved in food supply chain and recommended corresponding risk mitigation strategies.

Among many approaches, ISM has been effective in that it uses graphical representation of the SC capabilities of interest. Our intension here is to provide a set of decision measures for controlling and improving resilience of the companies in the chain and thus ISM is most appropriate for this research.

Our use is unique in that we utilize literature review instead actual expert's evaluation. Existing studies are based on theoretical and empirical evidences, thus we deem these studies to reflect larger number of experts versus a panel of experts that would have been adopted in order to construct initial matrix. Moreover, Rajesh's (2017) incorporated a validation stage to an existing ISM in order to assess and verify the proposed digraph by the panel of experts. Similarly, we verify our matrix based on a panel of SCM professionals with 10 or more years of experience in management. Final steps taken to achieve hierarchical relationship among SC capabilities are shown below:

- ***Step1: Identification of relevant elements.*** Based on systematic literature review, 14 SC capabilities that enable a suitable SC resilience level are identified in **Table A1**.
- ***Step2: Identify potential influential relations.*** Existing studies that explicitly examine SC elements or capabilities and SC resilience are identified to evaluate all potential influential relations and their interpretations, as shown in **Table A2**.
- ***Step3: Form an initial reachability matrix.*** Mark potential relations between the SC capability of A and B in the binary matrix (1 if relation exists, 0 otherwise) and visually represent influential relations in a direct reachability matrix, as shown in **Table A3**.
- ***Step4: Finalize reachability matrix.*** Based on the previously formed direct matrix, identify the transitive relations (i.e., if A affects B, and B affects C, then A affects C) to include significant transitive relations. **Table A4** represents the final reachability matrix of SC capabilities.
- ***Step5: Analyze hierarchical levels of SC capabilities.*** Based on the reachability, antecedents, and intersection elements, SC capabilities are sorted in a number of iterations to form a final hierarchical influence relation as shown in **Table A5 and A6**.
- ***Step6: Validation and finalization of digraphs.*** After sorting the SC capabilities at different levels, digraphs are used to depict hierarchical influence relations based on the final reachability matrix. The constructed digraph is validated by an expert panel of five SC experts with plausible work experiences with a survey listed in **Appendix A** which was accompanied with detailed definitions of constructs and its examples. The validated digraph representing the relations is shown in **Figure A3**.

Table A2. Interrelationship of SC capabilities based on literature reviews

	FLX	RED	VEL	VIS	COL	AGL	ROB	EFF	ALT	TEC	ALG	CUL	OPC	INF
FLX		21	1			6,14,21,22, 23,24,27,28, 29,32,33,41, 47,50		24,28, 39,43	6,21,50				20,49	
RED	6,30,31,34, 38,41,46		6,33	35			29	39	21				41,49, 51	
VEL	6					6,14,23,24,25,29,41,51		6,30						
VIS	1,3,37		1		1	6,22,29,41,51		15	6,7,15, 25,33, 36,50		15,39			
COL	1,4,9,14,18, 27,30,36,40, 44,45,47		1,14,30	6,15, 30		24,30,41	6,25,27	4,8,9, 18,27	6				14,33	29,36
AGL	41							32	21					33
ROB	19,27,28,39					23,24		35						
EFF	28,40,44					21,24	21,32, 35		21				51	
ALT	40			25		50							37	

Table A2. Interrelationship of SC capabilities based on literature reviews (cont.)

	FLX	RED	VEL	VIS	COL	AGL	ROB	EFF	ALT	TEC	ALG	CUL	OPC	INF
TEC	27,44,45			5,7,9, 17,33, 37,15	8,16, 17,31, 36,38	23,24,38		8,12,17	17,10		37		12,36	17,23, 36,44
ALG	27,30,40,45		30	30	4,6,25, 30	30,44	25	18	33,10				13	
CUL	19,20,45				9,13, 16	24,28		24,28					16	9
OPC	14,19,35,40		14			11,14,36, 41,50		11		13				
INF	4,12,14,27, 30,47		30	2,6,14,15, 27,30,36, 42	4,8,12, 30,44	29,33,43	5	4,5,8, 18,48	3,48,50			48	10,14, 26	

NOTE. Flexibility (FLX), redundancy (RED), velocity (VEL), visibility (VIS), collaborative (COL), agility (AGL), robustness (ROB), efficiency (EFF), alertness (ALT), technology competency (TEC), alignment (ALG), cultural competency (CUL), operational competency (OPC), information sharing (INF). 1 (Mandal, Sarathy, Korasiga, Bhattacharya, & Dastidar, 2016)*, 2* (Barratt & Oke, 2007)*, 3* (Wei & Wang, 2010)*, 4* (Cao & Zhang, 2011)*, 5* (Zacharia & Mentzer, 2004)*, 6* (Jüttner & Maklan, 2011)*, 7* (Francis, 2008)*, 8* (Sheu, Rebecca Yen, & Chae, 2006)*, 9* (Fawcett, Osterhaus, Magnan, Brau, & McCarter, 2007)*, 10* (Ponomarov & Holcomb, 2009)*, 11* (Zhou & Benton, 2007)*, 12* (Brusset & Teller, 2017)*, 13* (Pagell, 2004)*, 14* (Lin, Chiu, & Chu, 2006)*, 15* (Brandon-Jones et al., 2014)*, 16* (Rajaguru & Matanda, 2013)*, 17* (Boyson, Corsi, & Verbraeck, 2003)*, 18* (Danese & Romano, 2011)*, 19* (Eltantawy, 2016)*, 20* (Zsidisin & Wagner, 2010)*, 21* (L. Purvis et al., 2016)*, 22* (Baker, 2006)*, 23* (Swafford, Ghosh, & Murthy, 2006b)*, 24* (Narasimhan, Swink, & Kim, 2006)*, 25* (X. Li et al., 2017)*, 26* (Bhattacharya, Geraghty, Young, & Byrne, 2013)*, 27* (Stevenson & Spring, 2007)*, 28* (Laura Purvis, Gosling, & Naim, 2014)*, 29* (Hohenstein et al., 2015)*, 31* (T.J. Pettit et al., 2013)*, 32* (M. Gligor & Holcomb, 2014)*, 33* (Roberta Pereira, Christopher, & Lago Da Silva, 2014)*, 35* (Yang & Yang, 2010)*, 36* (Tachizawa & Gimenez, 2010)*, 37* (J. Blackhurst, Craighead, Elkins, & Handfield, 2005)*, 38* (Christopher & Holweg, 2011)*, 39* (Tang & Tomlin, 2008)*, 40* (Yi, Ngai, & Moon, 2011)*, 41* (Carvalho, Barroso, MacHado, Azevedo, & Cruz-Machado, 2012)*, 42* (Carvalho, Azevedo, & Cruz-Machado, 2012)*, 43* (Chiang, Kocabasoglu-Hillmer, & Suresh, 2012)*, 44* (Simangunsong, Hendry, & Stevenson, 2012)*, 45* (Virginia L. M. Spiegler, Naim, & Wikner, 2012)*, 46* (Rice Jr & Caniato, 2003)*, 47* (Blome, Schoenherr, & Eckstein, 2014)*, 48* (G. Li, Lin, Wang, & Yan, 2006)*, 49* (Chopra & Sodhi, 2004)*, 50* (X. Li, Goldsby, & Holsapple, 2009)*, 51* (Christopher & Peck, 2004)

Table A3. Initial reachability matrix of relations influencing SC capabilities

		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}
X_1	FLX	1	1	1			1		1	1				1	
X_2	RED	1	1	1	1			1	1	1				1	
X_3	VEL	1		1			1		1						
X_4	VIS	1		1	1	1	1		1	1		1			
X_5	COL	1		1	1	1	1	1	1	1				1	1
X_6	AGL	1					1		1	1					1
X_7	ROB	1					1	1	1						
X_8	EFF	1					1	1	1	1				1	
X_9	ALT	1			1		1			1				1	
X_{10}	TEC	1			1	1	1		1	1	1	1		1	1
X_{11}	ALG	1		1	1	1	1	1	1	1		1		1	
X_{12}	CUL	1				1	1		1				1	1	1
X_{13}	OPC	1		1			1		1		1			1	
X_{14}	INF	1		1	1	1	1	1	1	1			1	1	1

Table A4. Final reachability matrix (*=transitive link)

		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}
X_1	FLX	1	1	1	1*		1	1*	1	1	1*			1	
X_2	RED	1	1	1	1	1*	1*	1	1	1	1*	1*		1	
X_3	VEL	1	1*	1			1	1*	1	1*				1*	1*
X_4	VIS	1	1*	1	1	1	1	1*	1	1		1		1*	1*
X_5	COL	1	1*	1	1	1	1	1	1	1	1*	1*	1*	1	1
X_6	AGL	1	1*	1*	1*	1*	1	1*	1	1			1*	1*	1
X_7	ROB	1	1*	1*			1	1	1	1*				1*	1*
X_8	EFF	1	1*	1*	1*		1	1	1	1	1*			1	1*
X_9	ALT	1	1*	1*	1	1*	1		1*	1	1*	1*		1	1*
X_{10}	TEC	1	1*	1*	1	1	1	1*	1	1	1	1	1*	1	1
X_{11}	ALG	1	1*	1	1	1	1	1	1	1	1*	1		1	1*
X_{12}	CUL	1	1*	1*	1*	1	1	1*	1	1*	1*		1	1	1
X_{13}	OPC	1	1*	1	1*	1*	1	1*	1	1*	1	1*		1	1*
X_{14}	INF	1	1*	1	1	1	1	1	1	1	1*	1*	1	1	1

Table A5. Intersection of reachability and antecedent sets, and representation of level group 1

Enablers	Reachability	Antecedent	Intersection	Lvl.
X_1	1,2,3,4,6,7,8,9,10,13	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,3,4,6,7,8,9,10,13	I
X_2	1,2,3,4,5,6,7,8,9,10,11,13	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,3,4,5,6,7,8,9,10,11,13	I
X_3	1,2,3,6,7,8,9,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,3,6,7,8,9,13,14	
X_4	1,2,3,4,5,6,7,8,9,11,13,14	1,2,4,5,6,8,9,10,11,12,13,14	1,2,4,5,6,8,9,13,14	
X_5	1,2,3,4,5,6,7,8,9,10,11,12,13,14	2,4,5,6,9,10,11,12,13,14	2,4,5,6,9,10,11,12,13,14	
X_6	1,2,3,4,5,6,7,8,9,12,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,3,4,5,6,7,8,9,12,13,14	I
X_7	1,2,3,6,7,8,9,13,14	1,2,3,4,5,6,7,8,10,11,12,13,14	1,2,3,6,7,8,13,14	
X_8	1,2,3,4,6,7,8,9,10,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,3,4,6,7,8,9,10,13,14	I
X_9	1,2,3,4,5,6,8,9,10,11,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,3,4,5,6,8,9,10,11,13,14	I
X_{10}	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,5,8,9,10,11,12,13,14	1,2,5,8,9,10,11,12,13,14	
X_{11}	1,2,3,4,5,6,7,8,9,10,11,13,14	2,4,5,9,10,11,13,14	2,4,5,9,10,11,13,14	
X_{12}	1,2,3,4,5,6,7,8,9,10,12,13,14	5,6,10,12,14	5,6,10,12,14	
X_{13}	1,2,3,4,5,6,7,8,9,10,11,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14	1,2,3,4,5,6,7,8,9,10,11,13,14	I
X_{14}	1,2,3,4,5,6,7,8,9,10,11,12,13,14	3,4,5,6,7,8,9,10,11,12,13,14	3,4,5,6,7,8,9,10,11,12,13,14	

Table A6. Intersection of reachability and antecedent sets, and representation of level group 2 through 5

Enablers	Reachability	Antecedent	Intersection	Lvl.
X_2	2,3,4,5,7,11,13	2,3,4,5,7,10,11,12,13,14	2,3,4,5,7,11,13	II
X_7	2,3,7,13,14	2,4,5,7,10,11,12,13,14	2,7,13,14	II
X_{13}	4,5,10,11,13,14	2,3,4,5,7,10,11,12,13,14	4,5,10,11,13,14	II
X_3	2,3,14	3,4,5,10,11,12,14	2,3,14	III
X_{14}	3,4,5,10,11,12,14	3,4,5,10,11,12,14	3,4,5,10,11,12,14	III
X_4	4,5,11	4,5,10,11,12	4,5,11	IV
X_5	4,5,10,11	4,5,10,11,12	4,5,10,11	IV
X_{11}	4,5,10,11	4,5,10,11	4,5,10,11	IV
X_{10}	10	10	10	V
X_{12}	12	12	12	V

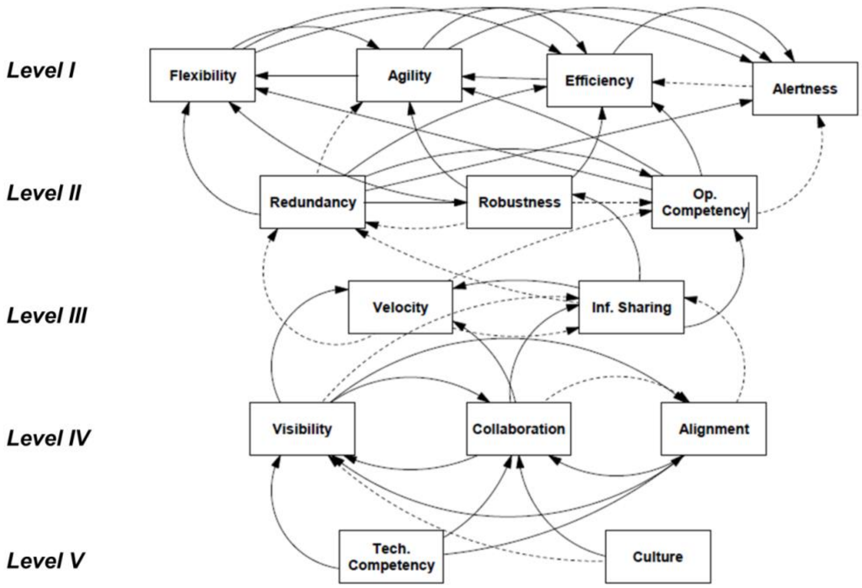


Figure A3. Digraph representing SC resilience capability relations

Based on the interpretive structural model analysis, we identified five levels of SC capabilities. The first level consisted of flexibility, agility, efficiency and alertness. These capabilities are placed at the highest level of partitions, with no farther reachable level available. Level 2 consisted of redundancy, robustness and operating competencies, followed by velocity and information for Level 3. Level 4 contained visibility, collaboration, and alignment, and finally, Level 5 is formed with technology competency and culture.

3.2.2 Study 2 – Hypothesis development of LMX, SC capabilities, and SC resilience relationships

With the top four SC capabilities identified in the previous section (flexibility, agility, efficiency, alertness) we now finalize a hypothetical model to observe efficiency relationships among LMX, SC capabilities, and SC resilience, as shown in **Figure A4**.

> **HYPOTHESIS 1 (a)-(d)** There is a positive relationship between the level of Leader-Member exchange relationship and the level of SC capabilities (flexibility, agility, efficiency, alertness)

> **HYPOTHESIS 2 (a)-(d)** There is a positive relationship between SC capabilities (flexibility, agility, efficiency, alertness) and SC resilience in post-disruption context

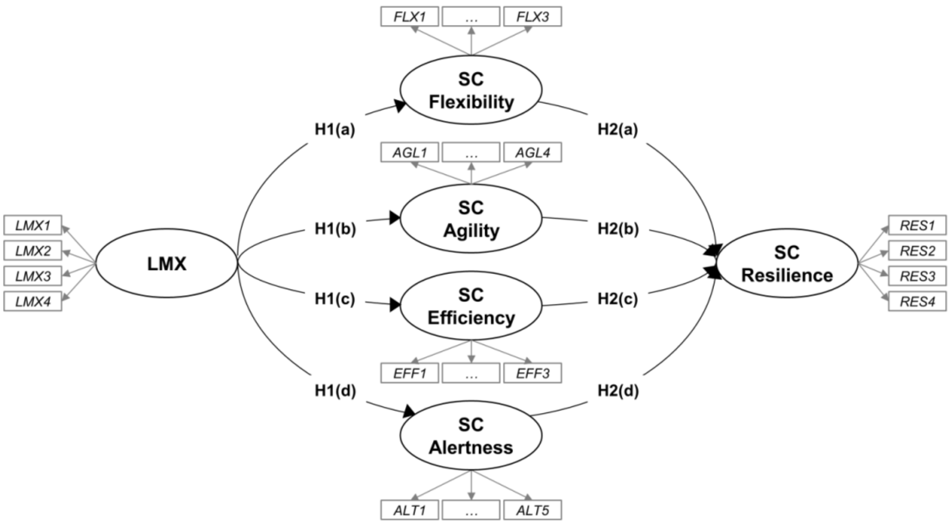


Figure A4. Final hypothesized LMX-SCRES model

To propose a comprehensive resilience model for SCM, we need to develop a measurement model with which a firm can evaluate its sustainability in terms of resilience. In essence, the resilience model of interest is nothing but a measurement system. The intention of this chapter is to set up a measurement system with which one can assess the level of SC resilience for timely adjustment. When designing a measurement system, it has been reported that the three requirements of representativeness, measurability, and repeatability must be satisfied.

Representativeness of a measure is needed to attain the initial goal of designing the measure. It should be able to provide a solid and appropriate assessment perspective for the distinctive activity. Measurability emphasizes the decision aspect of the measurement system. Without accurate assessment, any decision related to the measure might result in uncertain outcomes. The measures must guarantee accuracy and validity. The last requirement repeatability supports the managerial concerns in real world applications. The measurement system is often used on a continual basis for maintaining and improving the situation. Likewise, the comprehensive resilience model is supposed to be utilized over time as an effort to foster the desired level of resilience. The model can, of course, be used in making a series of quick recovery decisions when the SC capability is at critical risk.

By considering the three requirements—representativeness, measurability, and repeatability—in developing a new measurement system, we can come up with three requirements for a comprehensive model. First, the comprehensive model should cover all the key resilience attributes, if feasible, so that the users would not have to worry about any hidden attributes at the application stage. Second, the model should be justified in its measurability. No matter how well the attributes may be representing resilience, it is of no use if they are assessed in a formal way. Third, the attributes need to be presented in a conceptual framework. The concept model must be logical and practical for the practitioners who may apply the model for real world decisions.

3.3 Results and analyses

Using the candidate resilience attributes, a survey study is conducted to find out their representative status for the managers in the field of SC. In doing so, we can identify the criticality of the resilience factors and determine whether or not they need to be included in the comprehensive model.

3.3.1 Survey design and data characteristics

We performed survey analysis using professionals with SC experience from the following ten industries: (1) agriculture, forestry, fishery, mining, and manufacturing; (2) electricity, gas, waterworks construction, sewage, disposal, and environmental restoration business; (3) construction, (4) wholesale and retail, transportation, lodging and restaurant business, (5) publishing, video, broadcasting, communication and information service, (6) finance, insurance, real estate, (7) professional science and technology services, (8) public administration, (9) education services, arts and leisure related industries; and (10) all the others. This was done to both verify the scales' adapted psychometric properties and test the interrelationships. This consideration was important, as our study's sampling frame necessitated that individuals experience conventional e-commerce versus m-commerce, rather than offline versus online sites. We tested our hypotheses by consulting a nationwide surveying organization in three steps: (1) the listing of survey respondents; (2) screening; and (3) conducting the survey. First, a cross-sectional list of over 1,100 professionals with more than three years of experiences was created. A filtering process was used in the second step to remove those who did not have sufficient knowledge of SC process (ability to distinguish buyer-supplier relationship and involved in business transactional activities among SC members). After the screening process, we obtained a usable, stratified sample size of 228 respondents (20.7% response rate), who completed an online survey during the third step. The questionnaire was based on measures well established by assessment studies, as shown in **Appendix A2**, and was also translated into Korean by a professional language instructor to ensure consistent wording.

The characteristics of the subjects are as follows: gender (55% males); years of work experiences (50% more than 8 years; 18% between 6 and 8 years; and 32%

less than 6 years); and firm's type (14% worked at large corporations and 86% in small and medium enterprises).

3.3.2 Model reliability and validity

To confirm the measurement model's consistency with empirical data, we used AMOS 21.0. The latent constructs' measurements, as well as their loadings can be found in **Appendix A2**. Standardized loadings ranged from 0.86 to 0.92, were significant at $p < 0.01$. The model demonstrated acceptable fit indexes: $\chi^2 = 315.906$, $df = 200$, $p < 0.000$; Normed Fit Index (NFI) = 0.952; Tucker-Lewis Index (TLI) = 0.977; Comparative Fit Index (CFI) = 0.982; and Root-Mean Squared Error of Approximation (RMSEA) = 0.051. We further assessed both discriminant and convergent validities through a confirmatory factor analysis (CFA) using a maximum likelihood estimation regarding the nomological validity that was verified through a correlation matrix analysis of the constructs. **Table A6** indicates the results of convergent and discriminant validity. Cronbach's alpha values were greater than 0.7; thus, the assessment was reliable (Nunnally & Bernstein, 1967). The average variance extracted (AVE) values for each construct, shown within brackets on the diagonals, ranged from 0.78 to 0.83. As all exceeded 0.50, the constructs' convergent validity was supported (Fornell & Larcker, 1981). Construct reliabilities (CR) ranged from 0.82 to 0.93, substantially exceeding the recommended value of 0.70 (Gefen, 2000), thereby validating the constructs' unidimensionality. The latent constructs' reliabilities (i.e., Cronbach's alpha values) ranged from 0.93 to 0.95, in accordance with Nunnally's (1967) suggestion that each construct score should be greater than 0.60 to be considered reliable.

Discriminant validity was assessed by examining whether the AVEs' square roots (noted as the variables on the diagonal in **Table A7**) were greater than the squared multiple correlation (SMC) value shown below the diagonal (Fornell & Larcker, 1981). All correlations satisfied this condition, with the exception of the correlation with resilience and LMX. A chi-square discriminant validity test of the resilience and LMX constructs revealed that these were significantly distinct ($p < 0.001$). Additionally, a CFA with two separate constructs ($\chi^2 = 60.47$; $df = 19$; $p < 0.001$; NFI = 0.97; RMESA = 0.10; and CFI = 0.98) had a better fit index than a

CFA with two combined constructs (χ^2 = 160.24; df = 20; p < 0.001; NFI = 0.92; RMSEA = 0.18; and CFI = 0.93). This implies that the two constructs should be assessed separately.

Table A7. Composite reliability, Cronbach's α, convergent and discriminant measures for SC capabilities

Constructs	CR	α	X_1	X_2	X_3	X_4	X_5	X_6
Flexibility (X_1)	0.94	0.95	*(0.83)*					
Agility (X_2)	0.95	0.93	0.76	*(0.82)*				
Efficiency (X_3)	0.93	0.94	0.60	0.71	*(0.81)*			
Alertness (X_4)	0.95	0.93	0.53	0.65	0.73	*(0.79)*		
Resilience (X_5)	0.94	0.94	0.52	0.61	0.75	0.78	*(0.79)*	
LMX (X_6)	0.93	0.94	0.44	0.57	0.69	0.76	0.81	*(0.78)*

3.3.3 Structural effects

The results shown in **Table A8** indicate that the effects of flexibility and agility on resilience are insignificant. Thus, H2b and H2c are rejected. However, efficiency and alertness have significant impact on resilience, with loadings of 0.28 and 0.63, respectively. Moreover, LMX also showed a significant and positive effect on all capabilities, with loadings ranging from 0.74 to 0.94 and p-values less than 0.001.

Table A8. Results of hypothesized research models

Hypothesis				Loadings	SE	CR	*Sig.*	Result
H1a	LMX	→	Flexibility	0.74	0.07	12.22	0.001	Supported
H1b	LMX	→	Agility	0.84	0.07	14.01	0.001	Supported
H1c	LMX	→	Efficiency	0.90	0.06	15.18	0.001	Supported
H1d	LMX	→	Alertness	0.94	0.06	16.75	0.001	Supported
H2a	Flexibility	→	Resilience	0.00	0.07	-0.03	0.973	Not Supported
H2b	Agility	→	Resilience	0.07	0.09	0.77	0.444	Not Supported
H2c	Efficiency	→	Resilience	0.28	0.08	3.38	0.001	Supported
H2d	Alertness	→	Resilience	0.63	0.08	8.54	0.001	Supported

3.4 Discussion

3.4.1 Five partition levels of SC capabilities

Based on the interpretive structural modeling of existing SC resilience studies, we discovered that there are five partition levels. First level consisted of flexibility, agility, efficiency, and alertness. This was followed by redundancy, robustness, and operating competency as the second level. Third level consisted of velocity and information sharing, and the fourth had visibility, collaboration, and alignment. Finally, the fifth level consisted of competencies of technology and culture. This shows that there are far more complicated interrelationships among SC capabilities and that these need to be addressed prior to building a measurement model. For example, relevant indicators that were used to operationalize agility involved elements such as responsiveness, flexibility, information sharing, visibility, and velocity. While some studies, such as the flexibility-agility relationship by Chiang et al. (2012), explored agility as a part of SC performance or final output of the model, other studies viewed it merely as a mean to enable desirable outcome (e.g., agility-financial performance by Gligor et al. 2015).

While it may not be necessary to clearly differentiate the concepts of capabilities and performance, our findings suggest that SC capabilities should be treated on different levels, such as the strategic, tactical, and operational level (Carvalho, Azevedo, et al., 2012). Strategic teams can plan for the appropriate top tier of resilience enablers, which the operational team can then utilize as a base to specifically configure how to improve activities such as visibility and information sharing.

3.4.2 Insignificant role of flexibility and agility

The most surprising finding in this study is that flexibility and agility showed insignificant effect on SC resilience. A significant number of studies emphasized the importance of these constructs in SC resilience studies (Hohenstein et al., 2015). This result can be interpreted to be a result of inconsistency in the definition of resilience, as recently mentioned by Ali et al. (2017) and Kamalahmadi and Parast (2016). Ali et al. (2017) suggested that SC resilience capabilities should be distinguished as five different capabilities, that is, the ability to: anticipate; adapt; respond; recover; and learn. Moreover, these capabilities also affect specific dimensions of strategy and disruption phases, which finally lead to the expected outcome of SC resilience. As a result, flexibility and agility may not have been found to empirically affect resilience from the restorativity perspective, while they have been successful in improving it when viewed from the adaptivity perspective (Swafford et al., 2006b). Thus, we propose the following conceptual framework for further investigation of the effectiveness of flexibility and agility.

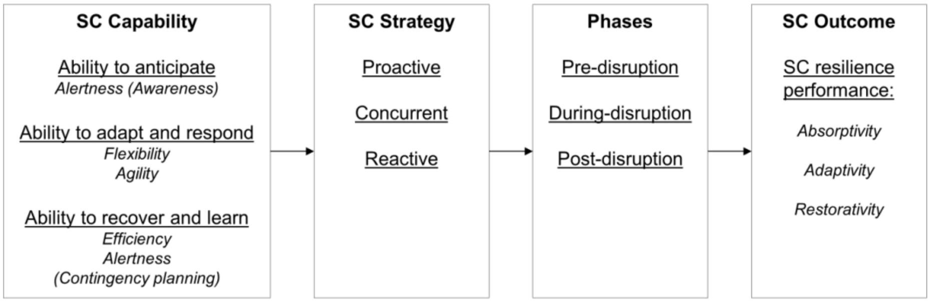


Figure A5. Proposed framework of phase-dependent SCRES relationship based on Ali et al.'s (2017) resilience map

3.4.3 Significance role of LMX on SC capabilities

The role of LMX, which depicts the level of a firm's perception and involvement with the key buying firm, significantly improves the SC capabilities of alertness, efficiency, agility, and flexibility, in the order given. Notably, both alertness and efficiency showed strong relationship with SC resilience. Thus, integrative improvement of LMX and SC capabilities can be expected to strengthen a firm's ability to deal and recover from the occurrence of unexpected events. Similarly, Capaldo and Giannoccaro (2015) investigated the effectiveness of trust on SC performance and showed the moderating role of structural relationships. Different structural relationships may impose a different number of SC leaders and place a firm in various complex leader-member relationships. As a result, a positive leader-member exchange relationship is essential in maximizing existing capabilities, which then lead to maximal resilience performance. In an effort to improve LMX, a firm may enhance management understanding with the key buying firm (the leader), by enlarging commonality in beliefs, expectations, and perceptions about risk management (G. Li et al., 2015). Also a firm may increase the coordination of time, effort, and financial investment to encourage the SC leader's relationship-specific investment for desirable outcomes (Henke Jr. & Zhang, 2010).

3.5 Conclusions, implications, and limitations

In the present study, we have focused on the role of exchange relationship in SC capabilities-resilience performance model. This is one of the first studies to introduce and empirically validate the significant role of leader-member exchange, and to highlight its effectiveness in improving SC capabilities. Moreover, we successfully demonstrated how to integrate the repository of literature and construct a fairly efficient model instead of building a model that uses more than 10 capabilities as potential determinants of the outcome of interest.

From a theoretical perspective, the exchange relationship theory that involves a leader-member exchange relationship is shown to be effective in improving overall SC capabilities. Without an understanding of the comprehensive role of relationships among firms, existing SC capabilities may not be able to fully explain SC resilience dynamics. From a managerial perspective, it is vital to understand that the optimal SC performance is achievable only through a collaborative effort. Specifically, in the context of post-disruption, a high perceived level of trust, respect, and obligation among the firms is necessary in order to collectively experience resilient performance.

Future research may investigate our findings further by using both theoretical and empirical approaches. First, future research could theoretically propose how different level of exchange relationship may affect different types of SC capabilities in a context such as innovation, rather than focusing merely on a common product-focused SC relationship. Second, we encourage future studies to theorize and empirically confirm how perceived exchange relationship between the firms (buying firm and supplying firm) comprehensively affects the SC resilience performance. Finally, it is recommended that future studies explore the causal relationships among SC capabilities and SC resilience based on different phases of a disruption (i.e., pre-, during-, and post-disruption). Both academic researchers and practitioners could benefit from a thorough understanding of system dynamics and performance behaviors in varying contexts.

CHAPTER 4

BICRITERION NETWORK RESILIENCE MODEL

A graphical relationship between firm's capabilities and network properties is proposed here to compute and visualize the entire supply network's resilience level. This model, which is called the bicriterion network resilience (BNR) model in this study, was originally inspired by the node-place model in transportation studies. The model utilizes each station's node value (the train station's capacity) and place value (surrounding environmental attributes) to identify and provide means for the improvement of stations (Bertolini, 1999; Papa & Bertolini, 2015). Similarly, we propose the network resilience model along with a concordance and discordance approach that can be used in prioritizing firms for balanced network resilient system.

4.1 Literature review

4.1.1 SC resilience from the perspective of networks

Supply network is represented by a "set of '*nodes*' that represent autonomous business units as firms who are able to exercise sovereign choices, and a set of '*connections*' that link these firms together for the purposes of creating products or services" (Hearnshaw & Wilson, 2013). Due to the nature of such network settings, interconnected firms can expect to receive benefits, such as innovation (Bellamy et al., 2014; Gao et al., 2015), and face risks, such as an increase in vulnerability (Wagner & Neshat, 2010; Yang & Yang, 2010). Specifically, Erol et al. (2010) stated that the extended enterprise structure may benefit from potential business opportunities through the increased level of connectivity. However, they may also suffer from being exposed to new threats.

Modern supply chain management (hereafter referred to as supply network or SN) has recently gained attention in theory and practice for its level of exposure to vulnerabilities. In particular, for supply networks that involve numerous overseas-based firms, every member in the network are largely exposed to hazards, strategic, financial, operational, infrastructural, and demand and supply vulnerabilities

(Chowdhury & Quaddus, 2015). While the speed of globalization (i.e., outsourcing R&D, sourcing from countries with lower) may be responsible for creating leaner supply chain (SC) setting, it also comes at a great cost of being too fragile to deal with disruptions (Christopher & Peck, 2004; Hendricks & Singhal, 2005; Wagner & Bode, 2006). Globalization creates SN relationship with elongated chains, which requires a high level of coordination to control for increased levels of uncertainty in inventory management (Greening & Rutherford, 2011). As part of the effort to deal with variety and levels of uncertainties, many studies have investigated and developed necessary capabilities that supply networks must acquire to remain resilient. **Table B1** lists the recent studies of resilience enablers.

Despite the consensus on the importance of a networks perspective, studies on SC sustainability and resilience have been limited to the analysis at the firm level. Moreover, while recent studies highlight theoretical and empirical findings with regard to SC capabilities and resilience, the need for managerial application guideline remains unclear.

Table B1. Recent resilience capabilities studies from supply network perspective (2015-2017)

Reference	Identified resilience enablers	Context	Methods	Managerial implication
(Brusset & Teller, 2017)	• External capabilities, integration capabilities, flexibility capabilities	• 171 managers in F&B, retail, general manufacturing in France	• Literature review-based ISM, Survey	• Integration and flexibility capabilities positively enhance resilience • Positive moderating effect of the perception of supplier/external risk on the relationship of integration/external capabilities and resilience
(Rajesh, 2017)	• Technological capability (SC design modification, supply flexibility, capacity enhancement, standardization, agility, collaboration, postponement, inventory, product rollover, pricing, planning)	• Electronics manufacturing in India	• Case study, total interpretative structural modeling	• Key influential technological capabilities are capability to modify SC design and planning capabilities
(X. Li et al., 2017)	• Preparedness, alertness, agility	• 20 different industries, 77 firms, in USA	• Survey	• Preparedness, alertness, agility positively affect firm's finical performance • Preparedness has a greater influence than alertness and agility suggesting the need for proactive approach
(L. Purvis et al., 2016)	• Robust, agile, lean, flexibility	• European premium drink producer	• Case study	• Framework of resilient supply chain strategy development and integration
(Eltantawy, 2016)	• Cultural competence, operational competence, situation awareness, access to keystone vulnerability	• n/a	• Conceptual study	• Proposition of supply management resilience as a multifaceted dynamic capability (engineering and ecological resilience) that aid the buyer's firm to ambidextrously adapt and transform in turbulent environments

Table B1. Recent resilience capabilities studies from supply network perspective (2015-2017) (cont.)

Reference	Identified resilience enablers	Context	Methods	Managerial implication
(Dabhilkar, Birkie, & Kaulio, 2016)	• Proactive-internal, proactive-external, reactive-internal and reactive-external resilience capabilities	• 22 different product lines	• Critical incident study	• Conceptualization of four supply-side resilience capabilities
(Ambulkar et al., 2015)	• SC disruption orientation, resource reconfiguration, risk management infrastructure	• 6 types of firm, 199 respondents	• Survey	• In a high impact disruption context, resource reconfiguration fully mediates the relationship between SC disruption orientation and firm resilience • In a low impact disruption context, SC disruption orientation and risk management infrastructure have a synergistic effect on developing firm resilience
(Hohenstein et al., 2015)	• Flexibility, redundancy, collaboration(visibility) agility(multiple sourcing), capacity, culture(inventory), information sharing	• n/a	• Literature review	• Most research has been qualitative and lacks in assessing and measuring SC resilience performance
(Scholten & Schilder, 2015)	• Collaborative activities (information sharing, collaborative communication, mutually created knowledge, joint relationship efforts)	• 8 byer-supplier relationships in the food processing industry	• Case study	• Identification of interdependencies of specific collaborative activities within the supply chain network

4.1.2 SC resilience studies by disruption phases

Existing studies on SC resilience often vary in terms of their points of view due to the growing interest in the different phases of experience in case of disruptive events. For example, traditional risk management studies mostly examined how to strengthen internal and external capabilities to minimize vulnerabilities as part of pre-disruption preparation. With the advancement of information technology, modern SCs or supply networks have begun to acknowledge the impacts of disruption and post- disruption phases.

The pre-disruption phase and the ongoing phase of disruption involves the ability to absorb shocks and adapt as a network and as a whole rather than individually. Sheffi and Rice Jr. (2005) identified two important variables that define firm's resilience performance: market positioning (the level of market power) and SC responsiveness (low or high). They proposed building redundancy and increasing flexibility as a means to obtaining SC resilience. Zhao et al. (2011) considered resilience as the availability of resources and connectivity and accessibility to interconnected firms. Using a military logistic network as a case study, they proposed new network resilience metrics for network suppliers. Johnson et al. (2013) examined the effectiveness of social capital (structural, cognitive, relational) on SC resilience (flexibility, velocity, visibility, collaboration) based on a case study.

The post-disruption phase often addresses the ability of a network to return to its original pre-disruption state or move to a better state. In the context of restorativity, Christopher and Peck (2004) proposed four key capabilities or principles for building SC resilience: SC reengineering, agility, collaboration, and risk aware culture. Ponomarov and Holcomb (2009) developed a conceptual model that reveals a positive causal relationship between logistics capabilities and SC resilience. Jüttner and Maklan (2011) performed case studies to understand how risk management (risk effect and knowledge management) improves SC resilience capabilities (flexibility, velocity, visibility, collaboration). Scholten and Schilder (2015) discovered that the positive impact of collaborative activities applies beyond the dyadic level, and it creates resiliency at the network level. Specifically, high level of collaboration is claimed to increase flexibility, velocity, and visibility.

Another branch of research focused on the characteristics of disruption and their effectiveness dependent on typologies of network structures. Ellis et al. (2010) empirically verified how the probability of disruption and the magnitude of impact encourage buyers to seek alternative suppliers. Based on a transaction cost economy and the resource dependence theory, they identified the characteristics of the supply market and the products that increase the likelihood and effectiveness of disruptions. Nair and Vidal (2011) simulated how network characteristics (average path length, clustering coefficient, size of the largest connected component, and maximum distance among the nodes) affect the robustness of supply networks (measured by insignificant differences in the mean of the performance measure). Kim et al. (2015) compared four fundamental SN structures to analyze the importance of node and arc disruptions vis-à-vis network-level disruption. They defined resilience as the likelihood of network disruptions given a certain node or arc being disconnected.

4.1.3 Social network theory based studies on network typologies

The structural relationship of supply networks has greater implications than a simple business connectivity representation. Based on the social network theory, firms can gain social capital through interaction among interconnected network relationships (Gao et al., 2015). Gao et al. (2015) identified the value of social capital in enabling greater accessibility to knowledge and resources that are not obtainable internally. Similarly, Arya and Lin (2007) empirically demonstrated that organizational performance (ability to acquire monetary and nonmonetary resources) is driven by both organizational characteristics and network structure (centrality and structural holes) in a non-profit industry. Network structure and its properties are expected to be highly influential when interconnected firms are required to commit cooperative efforts.

Network analysis not only helps visualize the complexity of overall partnership, but also provides visual support for the decision makers in preparing for supply network disruptions. For example, Basole and Bellamy (2014) created a visual decision support system for complex risk management and provided examples on how to systematically identify the level of global supply risk of a three-tier supply network. Bellamy et al. (2014) empirically demonstrated that (i) network accessibility positively drives innovation output; (ii) network interconnectedness moderates the accessibility-innovation relationship; and (iii) firm's absorptive capacity strengthens the effects of structural relationships on innovation output. Most recently, Kim et al. (2015) identified how SN structures influence disruptions, and the means to evaluate SN resilience level using graph theory. Assuming every firm (node) and its connection (link) has an equal probability of failure, they propositioned that network resilience is determined by the degree distribution. Hearnshaw and Wilson (2013) argued that an efficient SC follows a scale-free network based on key properties such as short characteristic path length, a high clustering coefficient, and a power law connectivity distribution. Thus, network structural design and its properties can shed light on resilience management of complex network from both theoretical and managerial perspective.

4.2 Methodology

In the current era of management, visual representation seems invaluable for diverse stakeholders to share their opinions based on the visual information. SCM managers, in particular, can benefit from the use of visual mechanisms in the communication process to mitigate constrained situations such as long distance, manager's varying perspectives, and ethical policies. For this reason, one of the key ideas of the resilience-based supplier improvement model under consideration is the inclusion of the concept of network based diagram.

Researchers state that supplier relationship can no longer be viewed as a chain-like linear relationship, but as a complex network relationship. This research is similar in terms of employing a network model, but it is different in terms of defining and integrating the resilience value (based on SC capabilities) and the network value (attributes of network structures). In this section, we first explain the adopted resilience attributes and then, describe how the types of network attributes were considered for this study. Finally, we provide a step-by-step prioritization order with a case example based on the concordance-discordance driven approach introduced by Rebai et al. (2006).

4.2.1 SC resilience capabilities

In this chapter, we are going to propose a network based representation model for SC resilience. The model deals with two important criteria; one for resilience and the other for network value. As for resilience, we have identified four key capabilities which are significant to resilience performance. Here, we explain the four capabilities in detail based on the existing literature, as they will be utilized in determining the level of resilience for each of the firms.

Flexibility

Flexibility is defined as the easiness of SC in altering the number and range of possible alternatives (i.e., number of possible alternatives and the degree of differences of alternatives) in order to cope with a variety market changes and events while delivering acceptable performance (Jüttner & Maklan, 2011). Specifically, L. Purvis et al. (2016) defined flexibility as the SC capability of modification or adaptation without trade-offs such as cost or long lead time. Similarly, Carvalho, Azevedo, et al., (2012), Jüttner & Maklan (2011), and Scholten & Schilder (2015) defined flexibility with the number of stable states a supply can readily take in response to number of changes that may arise. In another perspective, supplier's management of disruption and response to uncertain demands have been defined as a core capability of flexibility (Rajesh, Ravi, & Venkata Rao, 2015). To obtain flexibility from buyer's perspective, Hohenstein et al. (2015) emphasized the pertinence of obtaining flexibility through backup suppliers, production system and/or distribution channel (T.J. Pettit et al., 2013; Sheffi & Rice Jr., 2005; Tang & Tomlin, 2008). Lastly, Roberta Pereira et al. (2014) distinguished four main properties of SC flexibility in: sourcing flexibility, product flexibility, process flexibility, and transportation flexibility (Chiang et al., 2012; Timothy J Pettit et al., 2010; Rice Jr & Caniato, 2003; Simangunsong et al., 2012; Virginia L. M. Spiegler et al., 2012).

Agility

Not only increasing network complexity enhances vulnerability, but it also reduces SC agility (Yang & Yang, 2010). Agility is defined as the SC capability which enables timely response to actual changes by adapting SC process (X. Li et al., 2017). Notable literatures have interlinked agility and flexibility. For example, Jennifer Blackhurst, Dunn, & Craighead (2011) defined agility as a higher level of SC capability (compared to flexibility) that consists of visibility (i.e., communication and information sharing), velocity (i.e., acceleration and responsiveness) and redesign (i.e., supply chain redesign) elements. L. Purvis et al. (2016) described agility as a function of flexibility and that "agility tends to be used at a more encompassing, business wide level, with a focus on satisfying demand while flexibility tends to be used at a lower, more operational level" (Baker, 2006). On the other hand, Hohenstein et al. (2015) and Swafford, Ghosh, & Murthy (2006a) stated while agile supply chain must be flexible, flexible supply chain does not necessarily guarantee agility. Thus, flexibility and agility must be treated as two distinct capabilities. Specifically, several scholars considered the response speed inherent to SC agility (Manuj & Mentzer, 2008). G. Li et al. (2006) contended that agile firms must be able to respond to actual events or disruptions in a timely manner, and Christopher & Holweg (2011) stated that SC agility is a critical capability for the global sourcing process. As an example of agility practice, agile firm must carry safety stocks to buffer uncertain events in order to reduce the probabilities of stock outs and lost sales (Hohenstein et al., 2015).

Efficiency

Efficiency is defined as lean suppliers containing little or no excess actions which then enable utilization of extra capacity post disruptive phase (L. Purvis et al., 2016). Efficiency is often viewed along with robustness as robustness requires redundancy. However, during response and recovery phase to disruptions, efficiency plays a key role in minimizing overall financial loss and complementing other SC capabilities that contribute to resilience performance. The balanced level with efficiency has been identified in several SC capabilities focused studies. For example, redundant resources balanced with efficiency level is referred as a prerequisite to resilience (Scholten & Schilder, 2015). Moreover, flexibility attributes has also been advised to be equipped with efficiency for an effective response to disruptions (T.J. Pettit et al., 2013). Lastly, for SC velocity is built based on the SC efficiency in response and recovery (Jüttner & Maklan, 2011; Stevenson & Spring, 2007).

Alertness

With an increasing size of supply network, undermining alertness and awareness practice have been signified recently. Despite existing communication information system and routine among the network members, having a mode of alerting each other or monitoring process as a part of awareness practice is sometimes considered with little significance. Alertness is defined as the SC capability to detect changes, either from the surrounding business environment or from the internal SC network, in a timely manner (Eltantawy, 2016; X. Li et al., 2009, 2017). Both the buyer and supplier firms should be aware of various levels of risks, such as risks related with assets, process, organizations and environment (Rajesh & Ravi, 2015a). Awareness enhances preparation for the emergency cases, consequently, improving supplier's resilience capabilities (Rajesh & Ravi, 2015b).

4.2.2 Operationalization of resilience attributes (resilience value)

SC resilience measurements have been operationalized in two approaches: (1) subjective measurements of SC capabilities that enable resilience performance (Ambulkar et al., 2015; Pettit et al., 2013), and (2) objective measurements of capacities such as absorptive, adaptive, and restorative capacities, the sum of which gives the resilience performance (Cimellaro et al., 2016; Spiegler et al., 2016). However, Hosseini et al. (2016) emphasized that the performance measurement model and its accuracy becomes insignificant unless it is supplemented with an applicable planning policy. Hence, in this study, we focus on adopting and operationalizing subjective resilience attributes to stay within the study's scope of developing a resilience-based management policy.

We base abovementioned four resilience capabilities for the measurement model of *flexibility* (μ_1): "how easily can SCs change its volume and process?," *agility* (μ_2): "how fast can SCs respond and adapt?," *efficiency* (μ_3): " how easily can SCs alter due to lean management practices?," and *alertness* (μ_4): "how fast can SCs detect disruptive events?" It is important to note that the measurement can be based on both ordinal and cardinal scale measures.

4.2.3 Operationalization of network attributes (network value)

Various measurements of network attributes include average degree, network diameter, network centralization, network heterogeneity, degree exponent, and assortativity (Perera, Perera, & Kasthurirathna, 2017). We focus on social network theory driven node-level, specifically, degree of centrality and betweenness centrality from Kim et al. (2011). Similarly, network attributes can be assessed on both an ordinal and a cardinal scale. We adopt the author's measures for network characteristics at the node level as shown below.

Degree of centrality: Degree centrality of a node *i*, $C_D(n_i)$, is measured by the number of direct links that are connected to node *i*. x_{ij} is a binary value with 1 if there exists a link between node *i* and node *j*, and 0 otherwise.

$$C_D(n_i) = \sum_{j=1} x_{ij} = \sum_{j=1} x_{ji} \qquad \forall i$$

Betweenness centrality: Betweenness centrality of a node i, $C_B(n_i)$, is measured by the total number of links that contains node i. g_{jk} is the total number of geodesics (shortest paths) connecting two nodes, while $g_{jk}(n_i)$ is the number of those geodesics that contain n_i. n_i's betweenness is simply the probability that the node will lie between other nodes.

$$C_B(n_i) = \sum_{j<k} \frac{g_{jk}(n_i)}{g_{jk}} \qquad \forall i$$

We are mainly interested in these two attributes for the following reasons. First, most of the real-world network structures follow a scale-free model whose properties depend on the characteristic of the nodes (Perera, Bell, & Bliemer, 2017). Specifically, a scale-free model follows a power law distribution with a certain value of degree exponent that includes the node's degree growth rate with respect to network size. In practice, this is very useful as one can foresee whether a centralized (winner-takes-all) structure may eventually convert to a hub-and-spoke structure. Second, we temporarily disregard other metrics and attributes as their validity relies heavily on complete and accurate information regarding network system.

4.3 Bicriterion network resilience (BNR) representation

In this study, bicriterion network resilience model is considered to compute and visualize the resilience and network relations among firms. An ordering approach, concordance and discordance, is employed to determine the priorities of firms for enhancing the overall network resilience.

4.3.1 Network representation (illustration)

The supplier network considered in this study is an egocentric network. An egocentric network contains information that is related only to a focal firm (Kim et al., 2011). For example, such a network only captures direct and indirect relationships between buyers and suppliers, whose supply eventually reaches the final key buyer or an assembler, who then produces a final product for the customer market.

The network resilience representation in this study consists of nodes, links, and two node values. A node represents a specific firm in the SC, while links indicate the connectivity between the firms under consideration. Here, a link is interpreted as a simple business partnership, though it is extended to express interrelationships between two firms. The two node values are represented by a resilience value (μ) and a network value (γ), which simply indicate the firm's level of capability and structural exposure, respectively.

Evaluating resilience value (Resilience of firm *i*): The resilience value of a node i, μ_i, is measured by the weighted sum of resilience-focused capabilities of firm *i*, where k_{ir} represents the weight of capability *r*.

$$\mu_i = \sum_{r=1} k_{ir}\mu_{ir} \qquad \forall i$$

Evaluating network value (Network environment of firm i): The networks value of a node i, γ_i, is measured by a weighted sum of network attributes of firm i, where k_{it} represent the weight of network attribute t.

$$\gamma_i = \sum_{t=1} k_{it} r_{it} \qquad \forall i$$

$$where \qquad \sum_{r=1} k_{ir} + \sum_{t=1} k_{it} = 1$$

Along with these two criteria, the proposed network representation is called a bicriterion network resilience (BNR) model. Given that all the nodes of the network have two values, a resilience value and a network value, the level of SC resilience can be represented as a simple two suppliers–one buyer model, as depicted in **Figure B1 (A)**. **Figure B1 (B)** depicts a ten suppliers–one buyer network model that will provide the basis for the BNR model output in **Figure B2**.

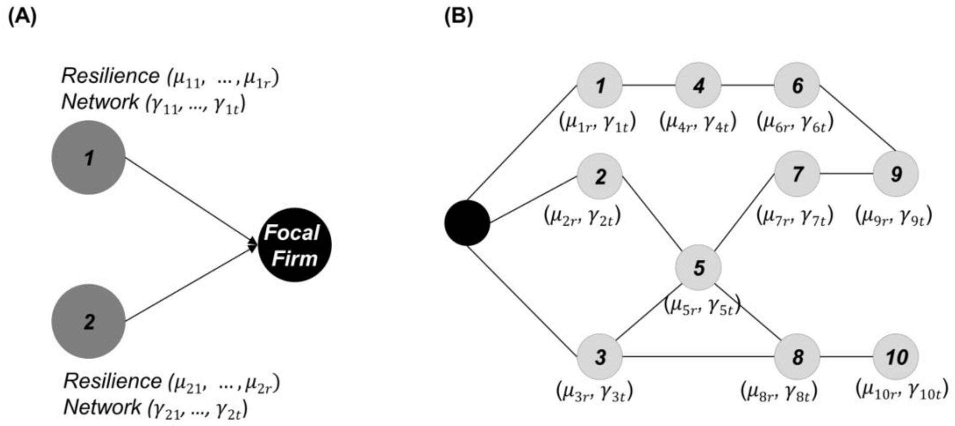


Figure B1. Illustrative examples of a model with two suppliers and one key buying firm (left) and a supply network with ten suppliers and one key buying firm (right)

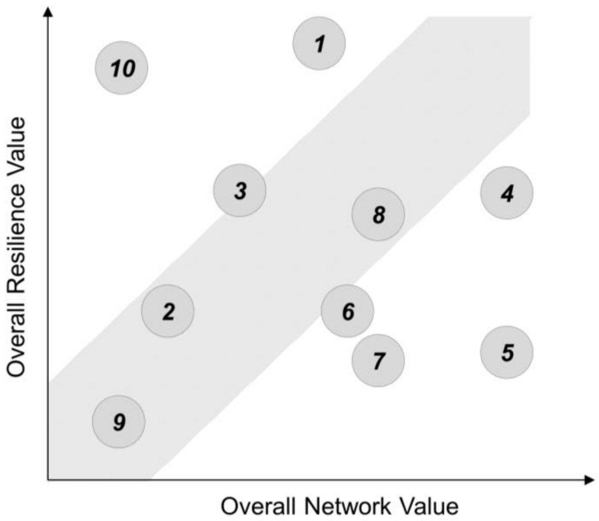


Figure B2. Illustrative output of BNR model based on resilience (y-axis) and network (x-axis) values

As illustrated in **Figure B2**, the *y*-axis value refers to the resilience capabilities of a firm (or the weighted firm's flexibility, agility, and alertness level), and in turn its readiness for disruptive events. The *x*-axis value refers to the network complexity level of a firm (or the firm's embeddedness and connectedness level in network), and in turn its exposure degree for disruptive events. The shaded region in diagonal depicts an ideal resilience zone. This is consistent with Bertolini's (1999) effort in including both node and its surrounding as a part of a transportation system.

This graphical representation can help practitioners understand their current status of SC resilience. However, the network must be utilized in the process of improving or maintaining the overall resilience of the network model. In this study, we introduce an approach that can be used in determining the priorities of firms.

4.3.2 Prioritization method: Concordance-discordance approach

The fundamental issue of the BNR model is that the two criteria (resilience and network values) have completely different, and often conflicting, aspects because the resilience value deals with subjective judgment of resilience, while the network value is based on the quantitative interpretation of network positional relationships.

It is our intention to propose a network model to achieve two goals: (i) understand the current level of suppliers' resilience and (ii) prioritize the firms (nodes) to maintain a balanced level of network resilience.

Among many prioritization approaches, we adopt the concordance and discordance approach (CDA). CDA was originally developed to assign ranking orders to a set of alternatives with multiple attributes, under the assumption that an ordinal rating is feasible for each alternative of a given attribute (Tsoukiàs, Perny, & Vincke, 2002).

Thus, in our study the resilience level can be obtained based on practitioners' ratings of interconnected firms for each of the determinant resilience attributes. Note that any quantitative (cardinal) assessment of resilience can be converted to an ordinal assessment. By utilizing such an advantage of the proposed approach, we can apply it to a variety of situations. We chose to adopt Rebai's (2006) approach to resolve a specific network management problem. In this study, we decided to use CDA for the following reasons:

1. It can deal with both ordinal and cardinal attributes in decision making. In SC resilience, practitioners may prefer diverse preference mechanisms based on which they indicate their varying preferences on the firms of interest.
2. There is virtually no limitations in the number of attributes to consider in the decision making process. Though we deal with a bicriterion network model here, we will demonstrate how the model can be generalized with multiple attributes in **Chapter 5**. There are multiple sub-criteria when considering resilience and CDA is deemed suitable as it does not limit the number of attributes.
3. The concept of concordance and discordance seems appropriate to SC resilience, since the interrelationships among the firms (or suppliers) are critical and often subject to positive (concordant) and negative (discordant) business relations.
4. Generally, other comparatively prioritization approaches are based on the evaluation of the distance to an ideal point which only represents the

positive situations of all attributes. Ideal situations of the attributes such as resilience and network value are ambiguous and difficult to specify, thus both positive and negative distances should be considered.

Now, we need to explain how one can make decisions in terms of prioritizing firms. This is important because the eventual goal of network representation is to help practitioners maintain a prescribed balance among the firms. In doing so, a confidence level on resilience can be justified. Here we set the problem as a bicriterion decision problem and prioritize the firms by a sequential screening process.

Step-by-step process for network resilience priority assessment:

Let N be a finite set of supply network connected nodes, C be a finite set of attributes of firm's value with given ordinal measurement scales, and k be an attribute weight vector such that $k(c) > 0$ for all $c \in C$.

Step 1: Identify the resilience and network values of each firm. For each supply network connected firm, n, evaluate c attributes based on the resilience and network values (μ, γ) and corresponding weights $k(c)$.

Step 2: Establish the concordance and discordance set of each firm. Calculate the level of superiority($S_c(n)$, S-count) and inferiority ($I_c(n)$, I-count) of each firm over other firms for each attribute c. Simply put, S-count is the number of firms for which firm n is superior to other firm such as b in terms of attribute c and I-count is the number of firms that are superior to node n in terms of attribute c.

$$S_c(n) = \{n \succ_c b\} \quad where\ n, b \in N$$

$$I_c(n) = \{b \succ_c n\} \quad where\ n, b \in N$$

Attribute c of a firm n can be interpreted as concordant if $S_c(n) > I_c(n)$, discordant if $S_c(n) < I_c(n)$,and neutral if $S_c(n) = I_c(n)$. A collective list of attribute c that belongs to the concordance set of firm n is denoted by $C^+(n)$, while the discordance set is denoted by $C^-(n)$, also known as positive and negative preference sets in this study.

Step 3: Establish the importance weight of concordance and discordance of each firm. Now, we measure the corresponding importance weights (π^+, π^-) based on the concordance and discordance sets $(C^+\ C^-)$ defined in the previous step. For node n, the total relevant concordance and discordance weights are calculated based on the following equation:

$$\pi^+(n) = \sum_{c \in C^+(n)} \pi_c$$

$$\pi^-(n) = \sum_{c \in C^-(n)} \pi_c$$

$$where\ \pi_c = \frac{k(c)}{\max\ k(c)}$$

Step 4: Establish the final weighted concordance and discordance level of each firm . With S-count, I-count, π^+, and π^- defined, we calculate the final weighted level of concordance and discordance level (χ^+, χ^-) of each firm:

$$\chi^+(n) = \sum_{c \in C^+(n)} (S_c(n) - I_c(n))\, \pi_c$$

$$\chi^-(n) = \sum_{c \in C^-(n)} (I_c(n) - S_c(n))\, \pi_c$$

Step 5: Finalize the weighted concordance-discordance matrix. Form a matrix based on π^+, π^-, χ^+, and χ^- to evaluate the agreement (conflicting) status between positive and negative perspectives.

Step 6: Develop the improvement order. Positive-value pairs of superior values with better performance are represented by (π^+, χ^+), while negative-value pairs of inferior values with better performance are represented by (π^-, χ^-). The improvement order is determined by the gap between the weighted concordance and discordance values, χ^+ and χ^-.

4.4 A case example

A prioritization approach to the proposed BNR model has been applied in a case example of the air conditioning division of a manufacturing firm in Korea called XYZ. This global firm manufacturers and markets display devices, home appliances, electronic parts, and software in the business divisions of home appliances, home entertainment, energy solutions, and mobile communications. XYZ is globally known for the high quality of its air conditioner, laundry machines, refrigerator, smart TVs, mobile phones, and its extensive global production and sales activities. With global sales worth 47.9 USD in 2016, XYZ is highly connected to a complex global supplier network. Thus, XYZ operates and assigns designated SN strategy teams for each division for risk and sustainability management.

Based on the interview with senior managers and team leaders of home appliance supply management division, 19 suppliers and their network structures have been identified, as depicted in **Figure B3**.

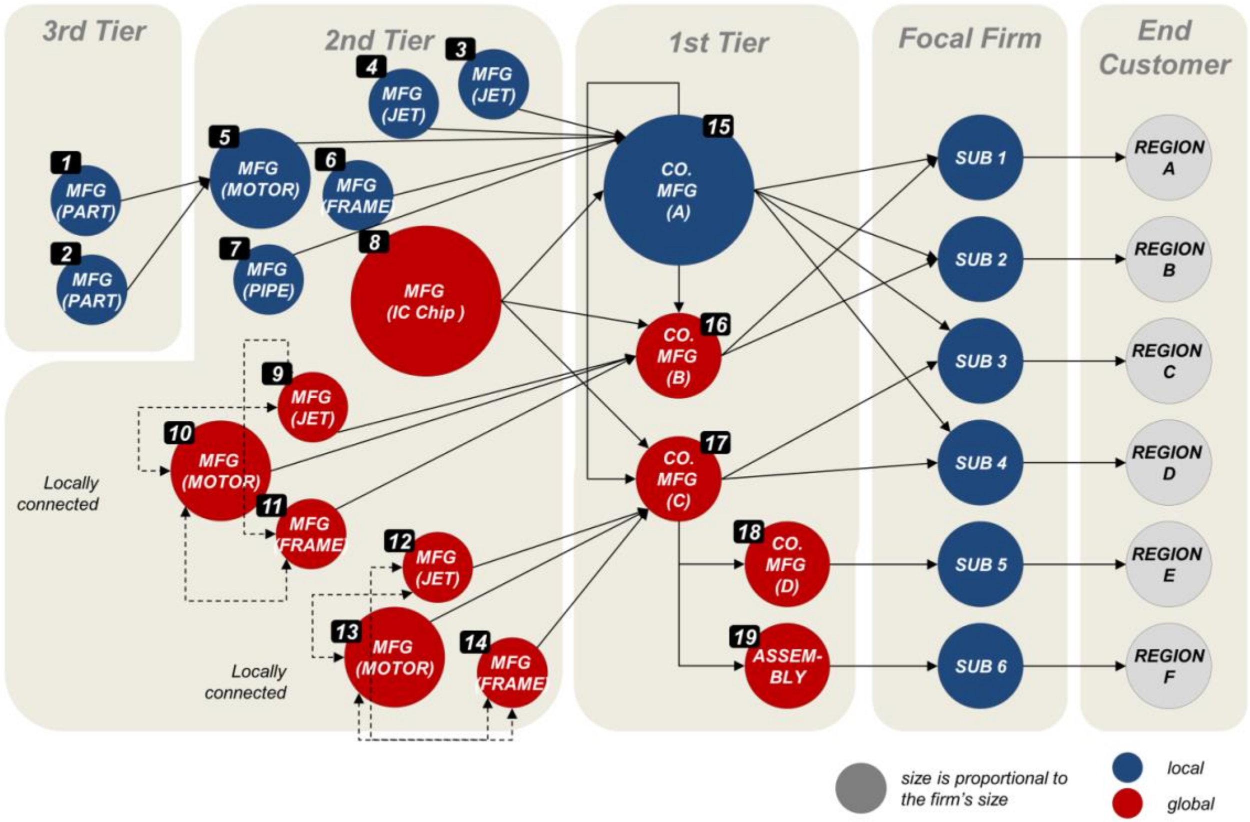


Figure B3. Case evaluated network structure

The characteristic of a network structure is that it indicates a mixture of centralized and potential block-diagonal relationships. Suppliers are divided into first to third tiers. The first tier consists of firm's own assembly and production sites both local and global. Notably, the sizes of firms 8 and 15 are significantly larger than the others as they primarily serve as main "hubs," acting as moderators in the network. Firms 9 to 11 and firms 12 to 14 are located near each other, displaying potential business or social relationships.

4.4.1 Prioritization assessment

In the following, we implement the step-by-step priority assessment explained in the previous section (hereafter, we will refer to a firm as a node to actively depict the network system's perspective):

Step 1: Consistent with the findings in **Chapter 3**, we adopt four SC capabilities as resilience values: flexibility, agility, efficiency, and alertness. For network value, we use the degree of centrality and the betweenness centrality. Each node is evaluated based on four capabilities ($\mu_{i1}, \mu_{i2}, \mu_{i3}, \mu_{i4}$) and network attribute (γ_{i1}, γ_{i2}) on a scale ranging from 0 to 10. In this case, we have a prior information matrix, as presented in **Table B2,** with equal weights for each attribute. Weighted averages of performance of attributes are also listed in the table.

Table B2. Prior rating information matrix of XYZ's connected nodes

Firm	Flexibility c_1 (μ_{i1})	Agility c_2 (μ_{i2})	Efficiency c_3 (μ_{i3})	Alertness c_4 (μ_{i4})	Degree of Centrality c_5 (γ_{i1})	Betweenness Centrality c_6 (γ_{i2})	Weighted average
k	0.167	0.167	0.167	0.167	0.167	0.167	-
1	9.0	7.0	4.0	5.0	8.89	10.00	6.5
2	6.0	7.0	6.0	4.0	8.89	10.00	6.0
3	6.0	4.0	1.0	2.0	8.89	10.00	3.5
4	8.0	8.0	10.0	10.0	8.89	10.00	9.3
5	0.0	9.0	9.0	8.0	6.67	6.60	8.2
6	8.0	8.0	6.0	10.0	8.89	10.00	8.3
7	7.0	5.0	7.0	5.0	8.89	10.00	6.3
8	0.0	6.0	3.0	10.0	6.67	10.00	5.6
9	5.0	7.0	3.0	10.0	4.44	10.00	7.6
10	2.0	4.0	10.0	5.0	4.44	10.00	6.6
11	2.0	10.0	1.0	9.0	4.44	10.00	6.9
12	0.0	10.0	1.0	2.0	4.44	10.00	4.6
13	8.0	7.0	6.0	6.0	4.44	10.00	8.1
14	8.0	10.0	5.0	5.0	4.44	10.00	8.4
15	3.0	2.0	8.0	10.0	0.00	0.00	10.8
16	5.0	4.0	2.0	5.0	3.33	9.06	5.9
17	0.0	2.0	7.0	7.0	1.11	2.26	8.2
18	1.0	3.0	1.0	4.0	7.78	10.00	2.8
19	7.0	6.0	5.0	1.0	7.78	10.00	5.3

Step 2: For each node, S-count ($S_c(n)$) and I-count ($I_c(n)$) are computed to represent how superior or inferior a node is compared to other nodes in the network. Based on the comparison of $S_c(n)$ and $I_c(n)$, we indicate the attributes that belong to the concordance (C) and the discordance (D) sets in the R-columns of **Table B3**.

Table B3. Counts matrix of $S_c(a)$ and $I_c(a)$ with its results in the R-columns

	RESILIENCE VALUE												NETWORK VALUE					
	c_1 (μ_{i1})			c_2 (μ_{i2})			c_3 (μ_{i3})			c_4 (μ_{i4})			c_5 (γ_{i1})			c_6 (γ_{i2})		
Firm	S_1	I_1	R_1	S_2	I_2	R_2	S_3	I_3	R_3	S_4	I_4	R_4	S_5	I_5	R_5	S_6	I_6	R_6
1	18	0	18C	9	6	9C	7	11	11D	5	9	9D	0	13	13D	0	4	4D
2	10	7	10C	9	6	9C	10	6	10C	3	14	14D	0	13	13D	0	4	4D
3	10	7	10C	3	13	13D	0	15	15D	1	16	16D	0	13	13D	0	4	4D
4	14	1	14C	13	4	13C	17	0	17C	14	0	14C	0	13	13D	0	4	4D
5	0	15	15D	15	3	15C	16	2	16C	12	6	12C	8	9	9D	16	2	16C
6	14	1	14C	13	4	13C	10	6	10C	14	0	14C	0	13	13D	0	4	4D
7	12	5	12C	6	12	12D	13	4	13C	5	9	9D	0	13	13D	0	4	4D
8	0	15	15D	7	10	10D	5	12	12D	14	0	14C	8	9	9D	0	4	4D
9	8	9	9D	9	6	9C	5	12	12D	14	0	14C	10	3	10C	0	4	4D
10	5	12	12D	3	13	13D	17	0	17C	5	9	9D	10	3	10C	0	4	4D
11	5	12	12D	16	0	16C	0	15	15D	13	5	13C	10	3	10C	0	4	4D
12	0	15	15D	16	0	16C	0	15	15D	1	16	16D	10	3	10C	0	4	4D
13	14	1	14C	9	6	9C	10	6	10C	10	8	10C	10	3	10C	0	4	4D
14	14	1	14C	16	0	16C	8	9	9D	5	9	9D	10	3	10C	0	4	4D
15	7	11	11D	0	17	17D	15	3	15C	14	0	14C	18	0	18C	18	0	18C
16	8	9	9D	3	13	13D	4	14	14D	5	9	9D	16	2	16C	15	3	15C
17	0	15	15D	0	17	17D	13	4	13C	11	7	11C	17	1	17C	17	1	17C
18	4	14	14D	2	16	16D	0	15	15D	3	14	14D	6	11	11D	0	4	4D
19	12	5	12C	7	10	10D	8	9	9D	0	18	18D	6	11	11D	0	4	4D

Step 3–Step 6: Based on the given rating information of nodes, we can now compute the importance weights (π^+, π^-) and the preferences (χ^+,χ^-), as presented in **Table B4** and **Figure B4**.

Table B4. Final concordant and discordant pair matrix table and prioritization order

Firm	$\pi^+(n)$	$\pi^-(n)$	$\chi^+(n)$	$\chi^-(n)$	Gap	Observation	Recommended Priority Order
1	9.33	4.33	522.67	112.67	410.00	Concordant	
2	8.17	5.50	400.17	181.50	218.67	Concordant	
3	5.17	8.50	160.17	433.50	-273.33	Discordant	6
4	12.50	0.83	937.50	4.17	933.33	Concordant	
5	9.00	8.33	486.00	416.67	69.33	Concordant	
6	11.33	1.83	770.67	20.17	750.50	Concordant	
7	8.83	5.00	468.17	150.00	318.17	Concordant	
8	6.50	7.50	253.50	337.50	-84.00	Discordant	9
9	7.17	6.17	308.17	228.17	80.00	Concordant	
10	6.17	7.33	228.17	322.67	-94.50	Discordant	7
11	6.83	7.00	280.17	294.00	-13.83	Discordant	10
12	4.00	9.33	96.00	522.67	-426.67	Discordant	5
13	8.33	5.17	416.67	160.17	256.50	Concordant	
14	8.33	4.83	416.67	140.17	276.50	Concordant	
15	6.00	11.17	216.00	748.17	-532.17	Discordant	4
16	4.17	12.67	104.17	962.67	-858.50	Discordant	2
17	4.33	12.83	112.67	988.17	-875.50	Discordant	1
18	4.00	10.83	96.00	704.17	-608.17	Discordant	3
19	7.00	8.00	294.00	384.00	-90.00	Discordant	8

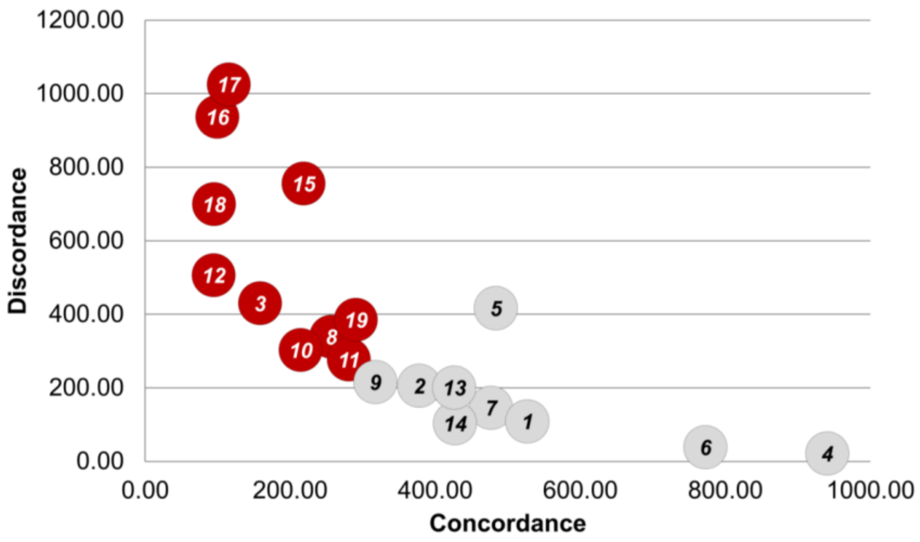


Figure B4. Result of concordance and discordance approach based prioritization order

4.4.2 Interpretation

Based on the results, we can observe ten nodes that display extreme discordance levels vis-à-vis concordance levels. A high discordance level and a low concordance level implies that these firms have significantly negative status of resilience and network values, thus requiring an improvement in the overall value of the supply network model.

The second set of firms that need attention are those with similar levels of concordance and discordance values. These firms indicate that although they perform better than others in some attributes, they perform worse than others in other attributes. This type of conflicting output imposes uncertain levels of performance when disruption occurs. Thus, these firms should be carefully monitored and accurately measured in terms of their resilience capabilities and network values.

Firms that indicate higher concordance values relative to discordance values are well-balanced firms that are most likely to continue performing in case of disruption. High levels of resilience and low levels of network embeddedness and connectivity will likely reduce their exposure to risks and mitigate vulnerabilities.

Comparison of weighted average based results and CDA based results are shown in **Table B5**. While the listed set of firms that need improvements are similar, the orders are noticeably different (i.e., 1st ranked improvement order for CDA and weighted average are firm 17 and firm 18, respectively). Whilst these minimal differences may appear insignificant, if the number of firms become excessively large or if the management is under heavy financial pressure, then such differences can be expected to enable efficient management.

Table B5. Comparison of firm's improvement prioritization order

Improvement order	First priority set	
	CDA based	Weighted avg. based
1	17	18
2	16	17
3	18	12
4	15	16
5	12	3
6	3	15
7	10	10
8	19	8
9	8	11
10	11	19

4.5 Conclusions, implications, and limitations

In this study, we first focused on developing an integrative model that encompasses objective and environmental attributes of supply networks. Each firm carries a certain potential for performance based on existing SC capabilities. Most importantly, the effectiveness of a firm's performance with respect to the entire SC may increase or decrease based on its embeddedness and connectivity within the supply network. Therefore, the bicriterion model is introduced to encourage a comprehensive outlook prior to SN management. Second, a concordance-discordance approach is adopted to identify firms that are uniquely conflicted (high discordance) in terms of performance levels vis-à-vis other connected firms. This approach is useful when delineating firms that may impose unexpected level of disruptions for given levels of capabilities.

From a theoretical perspective, both the resource-based view and the social network theory can shed light on different avenues on how to improve SC performance. While traditional studies on SCs proliferated in terms of identifying key SC capabilities that enable resilience and the implications of structural relationships of a network, an integrative outlook can surely provide a stepping stone to create a theory-based prioritization model. From a managerial perspective, the suggested model can not only objectively assess the performances and risk exposure levels of firms, but also effectively aid in identifying firms with balanced capabilities for a feasible amount of exposure to vulnerability or firms with unbalanced capabilities for high exposure to vulnerability.

While our study is one of the first to provide an integrative (resilience capabilities and network attributes) approach to the supplier improvement model, it has several limitations that need to be addressed in the future. Future studies are encouraged to investigate the following research questions with regard to the validity and generalizability of the model**.** (1) How accurately can the BNR model predict actual practitioners' qualitative perspective? Is the priority assessment of network model expected to change dependent on industry type? It is important to adjust the model accurately with respect to a real-world perspective. (2) How do the values of networks and resilience change as network structures change? The design of network structures will vary dependent on the industry or a firm's strategy. Thus, the validity of the model can be tested in varying network settings. (3) How would the resilience model change with respect to different cultures or exchange relationships? We recommend future studies to include cultural or exchange relationships in the resilient management model. Hohenstein et al. (2015) noted that culture-specific research on global SCs can improve SC resilience strategies in varying national cultural context. Although modern SCs call for complex global relationships, that is, an exchange relationship, whether it is based on cultural or regional differences should be evaluated further.

CHAPTER 5
TOTAL NETWORK RESILIENCE MODEL

A comprehensive network system is proposed by incorporating the leader-member exchange (LMX) concept into the network model that is called the total network resilience (TNR) model. The TNR model incorporates all the nodes and links that carry meaningful information for representing supply chain (SC) resilience. Here we used links to indicate the level of LMX among the firms in a SC context, and the nodes represent the level of suppliers' resilience. We extend the TNR model to create a probabilistic model, in order to show that the proposed model is applicable in uncertain situations. A series of sensitivity studies is also conducted.

5.1 Literature review

5.1.1 Leader-member exchange theory and exchange relation theory

A supply network (SN) may behave and operate on the basis of the types of contracts made among the firms, but SN resilience is bound to be affected by the social relationships formed by the parties. The LMX theory describes that successful leadership is achieved when both the leader and followers develop a mature partnership that enables various benefits (Graen & Uhl-Bien, 1995). As shown in **Figure C1**, this study intends to: extend (A) "LMX in organizational (personal)-level situation" to (B) a "SC LMX (SLMX) in a firm (supplier)-level situation" by substituting the personal members with firms in the SN. (Note that we use SLMX in place of LMX in the firm-level situation for clarity.) Although LMX was originally introduced in the literature of organizational behavior management, the concept has lately been employed in the SN context, both directly and indirectly. For example, I. L. Wu, Chuang, & Hsu (2014) observed both the supplier's perspective (trust, commitment) and the buyer's perspective (reciprocity, power) to evaluate the effectiveness of collaboration and information sharing practices on SC performance.

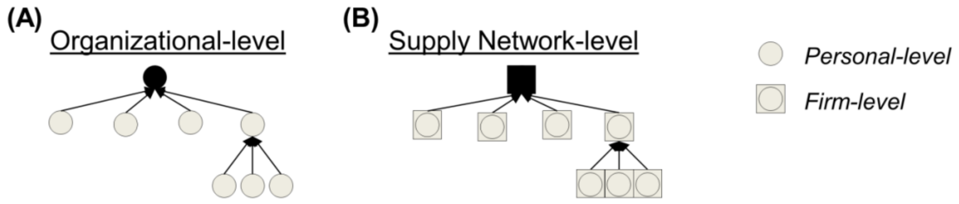


Figure C1. Visual representation of LMX in organizational- and supply network-level

The three reasons for extending the concept to SN are as follows. First, SLMX infers SN member's perceived maturity of partnership with the SN leader (or focal firm). Despite the level of channel power that a SN leader or focal firm may hold, it is exposed to relational evaluation by the SN members (or suppliers). Exchange relationships between the leader and member produces social credit that can contribute to SN members’ perceived social indebtedness; in turn, this could either encourage or discourage member’s compliance with the leader’s request (Grienberger, Rutte, & van Knippenberg, 1997). Similarly, a high level of SLMX will include high-quality relationships, which are characterized by mutual trust, commitment, and long-term relationship (Chang, Ellinger, Kim, & Franke, 2016).

Second, a SN member with a high level of SLMX shares higher norms and values with the SN leader. The outcome of relational evaluation may lead the SN leader to gain benefits by building a stronger business relationship, or a skeptical one that is strictly built on a transactional short-term relationship, with no long-term orientation. The high level of commitment enables members’ acceptance of norms and values, and thus, builds stronger intrinsic ties with the focal firm’s goals (Huo, Ye, Zhao, & Shou, 2016).

Third, suppliers with a high level of SLMX may exhibit a stronger desire to aid and support the SN leader in case of disruptive events. Specifically, in case of risk management, the SN leader will almost always depend on existing suppliers’ capabilities and their willingness to actively support, with or without a financial obligation. To prioritize the partnership value over its own benefit, the focal firm must encourage the SN member’s dedicated commitment to the relationship (van den Hooff & de Leeuw van Weenen, 2004). Thus, the high level of SLMX among all SC members is a strongly desirable attribute from the perspective of the SC leader, especially when the SC is exposed to vulnerabilities.

To further validate the applicability of SLMX in SN resilience context, six key questions relevant to it are interpreted in detail in **Table C1**. One may consider the interpretations as the assumptions under which the TNR model proposed here is applicable in reality. For example, leadership is interpreted as a significant impetus for directing and managing, while achieving impactful SCM performance based on the ability to create trust, respect, and mutual obligation that influence the SC partnerships (Sharif & Irani, 2012). It is quite common to interpret leadership not only for a group of individuals, but also for the interrelationships among organizations.

Table C1. Extended SLMX conceptual framework (Graen & Uhl-Bien, 1995) in SC context

Relevant questions to LMX	Interpretation in SC context
Definitions	
What is leadership	• A significant impetus for directing and managing while achieving impactful SCM performance based on ability to create trust, respect, and mutual obligation that influences SC partnerships (Sharif & Irani, 2012)
Who is the leader?	• An "instinctive" leader with financial power and/or exceptional knowledge of final products and services who is responsible for coordinating and overseeing the whole supply chain (Melnyk et al., 2009)
Who is the member?	• Anyone who is involved in a supplier-buyer relationship but not a leader
Application of LMX view in SC context	
What are the advantages?	• Accommodates differing needs of SC members, and can elicit superior work from different types of firms
What are the disadvantages?	• Time-consuming, relies on long-term relationship between specific leaders and members
When is appropriate for the application?	• When the relationship is potentially exposed to extraordinary events such as disruptive or adversity events

5.1.2 Relational studies in SN context

Although there are a number of relationship types in the existing literature, LMX has been chosen for extension in this study. The benefits of the adaptation of LMX as SLMX for SN resilience need to be explained. The investigation of the level of exchange relationships and their effectiveness in building SN competitive advantage has been studied comprehensively in many past studies. Initially, Hult, Ketchen, & Nichols (2002) found that "cultural competency," including learning within a SC, effectively reduces the cycle time. Moreover, Malhotra, Gosain, & Sawy (2007) established that a firm's adaptation to its environment can be improved by external knowledge. The characteristics and activities of such firms that enhance SN competitive advantage started becoming specific. For example, Kwon & Suh (2005) clarified that "trust" and cooperation" must be viewed separately, and that the SC must strive to improve the level of trust among the SN members. They indicated that a partnership based on a high degree of trust enhances the willingness to take risks, ultimately increasing overall SN performance.

Most recently, Roldán Bravo, Ruiz Moreno, & Llorens-Montes (2016) emphasized the role of "external knowledge" provided by customer, suppliers, universities, and even the competitors, in enhancing SC competence. Specifically, the firm's capacity to exploit external knowledge drives SN competency in the open innovation context. Huo et al. (2016) defined that "organizational commitment" plays a critical role in achieving SCM success. Organizational commitment, measured by a staff's commitment to a long-term relationship with the firm, has been found to positively drive SC integration, internal integration, and customer integration. Moreover, Chang et al. (2016) stated that a strong relationship between partners offers strategic and complementary relational resources that encourage specific behaviors such as communication, information sharing, and joint coordination of relevant processes. Consequently, a valuable relationship quality can effectively reduce opportunistic behaviors and maximize performance-related payoffs in a SN.

Besides SLMX, various theories and approaches relevant to the analysis of interrelationships among firms are listed in **Table C2** and the typologies are compared by highlighting their research (or investigation) orientation (resource, relationship, focal firm, and suppliers). It can be observed that SLMX includes all the orientations, and therefore, has a range of applications. To the best of our knowledge, this study is one of the first to contribute to the SC literature by refining SLMX and incorporating it into a network resilience model.

Table C2. Comparison of relational theories and research orientations

Relevant theories	Orientations				Examples
	Resource	Relationship	Focal firm	Suppliers	
Resource-based theory	O[A1]				(Gold, Seuring, & Beske, 2010; Richey, Adams, & Dalela, 2012)
Resource-advantage theory	O[B1]				(Hunt & Davis, 2012)
Relational view		O[C1]			(Zacharia, Nix, & Lusch, 2011)
Dynamic capability view	O[D1]				(Fawcett, Wallin, Allred, Fawcett, & Magnan, 2011)
Stakeholder theory		O[E1]			(Co & Barro, 2009)
Signaling theory		O[F1]	O[F2]		(Wagner, Coley, & Lindemann, 2011)
Force field theory			O[G1]		(Fawcett, Waller, & Fawcett, 2010)
Transaction cost theory			O[H1]		(Yigitbasioglu, 2010)
Contingency theory		O[I1]	O[I2]		(Danese, 2011; Hall, Skipper, Hazen, & Hanna, 2012)
Social exchange theory		O[J1]	O[J2]	O[J3]	(I. L. Wu et al., 2014)
SLMX view (Applicability dimension)	O (SC Capabilities)	O (Transactional value)	O (Expected LMX)	O (Perceived LMX)	Our Study

NOTE. A1: strategic purchasing and supply, corporate environmental proactivity; technological innovativeness, technological complementarity, flexibility. B1: financial, physical, legal, human, organizational, informational and relational resources that enable efficient and effective performance. C1: relational outcomes (honesty, trust, feeling, commitment). D1: SC collaboration. E1: perceived relative power, perceived urgency, perceived legitimacy. F1: trust in supplier, dependence on supplier, relationship length. F2: outcome fairness, relationship continuity, future collaboration. G1: cultural resistors, structural resistors. H1: intensity of information sharing. I1: product diversity, demand elasticity, spatial complexity. I2: contingency planning effectiveness. J1: information sharing, collaboration. J2: reciprocity, power. J3: trust, commitment

5.2 Development of total network resilience (TNR) model

5.2.1 Incorporation of SLMX into a network perspective

As Soosay & Hyland (2015) emphasized, dyadic approaches can provide valuable insights into collaboration among the firms in a SC context. The objective of bringing SLMX into the SN resilience framework is to help the practitioners determine priorities of the firms under consideration based on diverse aspects. Here we incorporate SLMX into the bicriterion network resilience (BNR) model, which was proposed in **Chapter 4**.

Having been able to justify the applicability of SLMX to the SC context, the process incorporating SLMX into the BNR model is straightforward. We, first, elaborate on the four stages in the development of exchange relationship for supply networks explained by Graen and Uhl-Bien (1995), and illustrated in **Figure C2**, so that the overall framework of BNR can be maintained as far as possible.

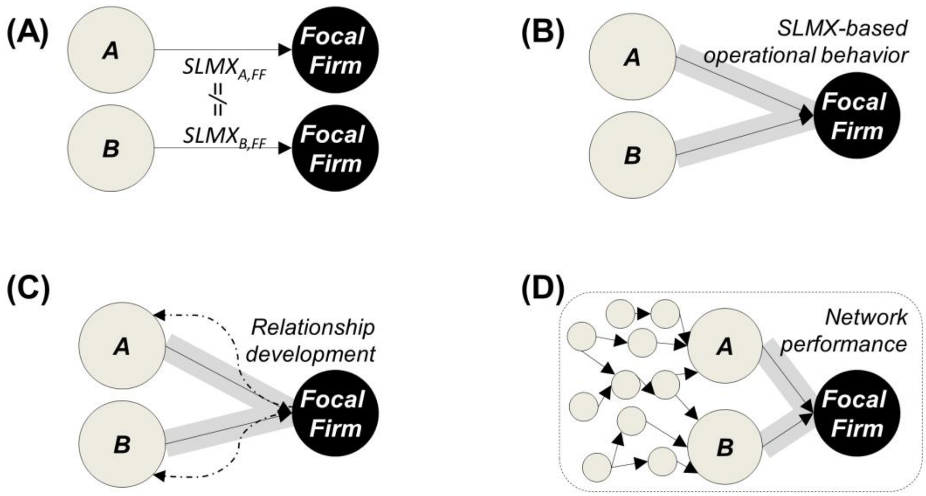


Figure C2. Development stages of SLMX relationship

- ***Stage 1: Identification of different dyadic relationships in multiple suppliers-one buyer SC structure.*** The focal firm ("the leader") has different levels of SLMX relationship with Supplier A and Supplier B ("the members"), as shown in **Figure C2 (A)**. Theoretically, a "high-quality exchange" relationship depicts whether the members would go beyond their contracted responsibility to act as "trusted assistants" to the leader. In a "low-quality exchange" relationship the members perceive their roles as being only "hired hands" and nothing more. Thus, the leader must decide the number and the strength of desired exchange relationships to nurture, based on the tradeoffs between the limited resources and the outcome of investments.

- ***Stage 2: Understanding the SC outcome based on the dyadic exchange relationships.*** Depending on the level of exchange relationship, the members may respond differently to the leader's needs, as shown in **Figure C2 (B)**. The behavioral decisions made by the SC leader and members are likely to determine the SC outcome, and ensuring the effectiveness of relationships is imperative as it ultimately influences the performance of the entire SC.

- ***Stage 3: Improving exchange relationships as a partner rather than as a buyer.*** Despite the traditional buyer-supplier relationship, which has the undesirable feature of distinguishing between the roles of superior and subordinates, the theory highlights the significance of developing a business partnership among the connected firms, as shown in **Figure C2 (C)**. The transition to the partnership perspective provides two major benefits—highly aligned process and the potential enhancement of SC capability. When the mutual partnership value increases, it evolves into a "mature partnership," which allows the SC members to share a relationship with the leader that is based on mutual respect, trust, and obligation. Consequently, both the leader and members are able to expect loyalty and support from each other.

- ***Stage 4: Expanding exchange relationships to a network level.*** Previous stages explore the role of SLMX based on the dyadic relationships formed within a simple buyer-supplier structure. We can now illustrate multiple dyadic relationships in a SN context, as shown in **Figure C2 (D)**. In fact, this final stage is the most generic situation considered in this study.

Since we are dealing with a complete network model, it seems appropriate to assume that all the SLMX levels are included in network performance assessment stage. In other words, the level of SLMX for each of the links is a fixed constant, which provides the likelihood of the SN member being supportive as expected by the leader. (i.e., SLMX is the probability that the normal business relationship is maintained during a given disruptive event.) Though there might be some variations in the interpretation of SLMX, we have chosen the probability assessment in order to further generalize the model into a probabilistic model in the next section. In short, the level of the SLMX for a given link from node i to node j is defined as follows:

$$The\ level\ of\ SLMX = \tau(i,j)$$

Given the SLMX, $\tau(\mathrm{i},\mathrm{j})$, for all the links, we can form a comprehensive network resilience model. Prior to formulating a TNR model, we would like to note one critical issue. To aggregate the incoming SLMX levels that a node (here a firm) receives, we need to know the relative weights associated with the incoming links. Such relative weights can be determined by transactional weight, final production part responsibility, revenue contribution amount, the level of contractual binding, or even as simple as focal firm's caring value. We define the relative weight value for each of the links as follows:

$$The\ level\ of\ transaction\ weight\ between\ node\ i\ and\ node\ j\ = w(i,j)$$

$$where \qquad \sum w(i,j) = 1 \qquad 0 \le w(i,j) \le 1 \qquad \forall i,j$$

Provided that all the information regarding SLMX and relative weights (here transactional weight) of the links is available, it is possible to finalize the total network resilience model.

5.2.2 The Structure of Total Network Resilience Model

We now propose a total network resilience model (TNR) for the enablement of the SN resilience. The term "total model" is used to emphasize that the system tries to consider simultaneously all the relevant resilience attributes, in addition to the two key attributes—SLMX and network value—for the network representation. It has been our intention to develop a model which enables the practitioners to make decisions based on SN resilience, which is evaluated by using existing information on SC capabilities and exchange relationship characteristics.

We make the following assumptions to ensure the robustness of the proposed TNR model: (1) the investigated SN structure is fixed, and represents ego-centric network property, and therefore, only includes information about connected firms and links that are relevant to the focal firm; (2) SN members have sufficient knowledge about existing SN resources and capacities in order to evaluate their capabilities; and (3) the characteristics of SLMX are such that it follows the conditions that are similar to those in LMX.

The TNR representation of a simple buyer-supplier model is illustrated in **Figure C3**.

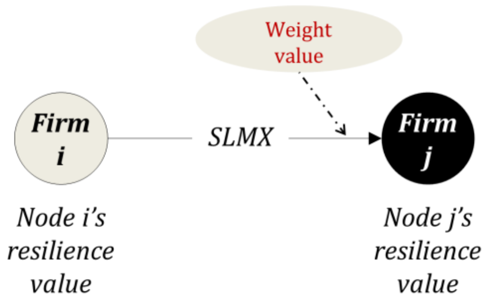


Figure C3. Conceptual Total Network Resilience (TNR) model

By applying it to a network, the TNR model becomes a network problem with three criteria—resilience, network value, and average SLMX. The objectives of the problem are to maximize the resilience, balance network value, and maximize the level of SLMX of the network nodes that are connected.

This effort can, in turn, lead us to employ the same prioritization methodology, Concordance and Discordance Approach (CDA), used previously in **Chapter 4**. CDA, which has been used for prioritizing the firms with two criteria, can also be directly applied for resolving the TNR model. Here we now set the problem as a multiple criteria decision problem and prioritize the firms by a sequential screening process. It is noted that the prioritization process of the TNR model is virtually identical to that of the BNR model used in **Chapter 4,** except that the former has three criteria and the latter has two.

Step-by-step process for TNR priority assessment by using a CDA approach:

Let N be a finite set of SN connected nodes; C be a finite set of attributes of node's value with given ordinal measurement scales; and k be an attribute weight vector such that $k(c) > 0$ for all $c \in C$.

- ***Step 1: Identify the resilience, network, and SLMX values of each node.*** For each SN connected node, n, evaluate c attributes based on the resilience, network, and SLMX values (μi, $\gamma i, \tau i$) and corresponding weights $k(c)$.
- ***Step 2: Establish the concordance and discordance set of each node.*** Calculate the level of superiority ($Sc(n)$, S-count) and inferiority ($Ic(n)$, I-count) of each node over other nodes for each attribute c.
- ***Step 3: Establish the importance weight of concordance and discordance for each node.*** Now, we measure the corresponding importance weights (π^+, π^-) based on the concordance and discordance sets (C^+ C^-) defined in the previous step. For node n, all the relevant concordance and discordance weights are calculated.
- ***Step 4: Establish the final weighted concordance and discordance level of each node.*** With S-count, I-count, π^+, and π^- defined, we calculate the final weighted level of concordance and discordance level (χ^+, χ^-) of each node.
- ***Step 5: Finalize the weighted concordance-discordance matrix.*** Form a matrix based on π^+, π^-, χ^+, and χ^- to evaluate the agreement (conflicting) status between positive and negative perspectives.
- ***Step 6: Develop the improvement order (first and last-order dominance).*** Positive-value pairs of superior values with better performance are represented as (π^+, χ^+), while the negative-value pairs of inferior values

with better performance are represented as (π^-, χ^-). The improvement order is determined according to the same procedure introduced for the BNR model.

For the sake of brevity, we do not present the prioritization process, as in **Chapter 4**. It is believed that the TNR model can deliver the benefits and strengths of the approach previously mentioned with the BNR model.

5.3 The TNR model – A probabilistic model

5.3.1 Conceptual framework

The TNR model proposed aforementioned is represented as a deterministic model, where both resilience and network values are fixed. However, the resilience capabilities may be uncertain and can be viewed as probability functions. Besides, the most critical concern from the point of view of the top management of the focal firm revolves around the probability that the supply network functions as expected, despite the disruptive event. Therefore, there is a need to develop a probability model for the deterministic TNR model.

Since SLMX has already been expressed as a probabilistic function, we now transform the TNR to a probabilistic model by treating the resilience capability level as a random variable. The network value is no longer meaningful because all the probabilities of the nodes and links are aggregated to compute the probability of maintaining SC resilience. The level of resilience at node i can be defined as follows:

$$P(n_i) = Pr(survival\ likelihood\ of\ node\ n_i) \quad \forall i \quad where\ n \in N$$

In this study, resilience at each node consists of four independent capabilities—flexibility, agility, efficiency, and alertness. We follow the approach of Hosseini & Barker (2016) in developing a probabilistic model of supplier evaluation. They assigned probabilistic values to a variable that can explain how one criterion would behave given how other variables behaved. For example, the likelihood of the primary criterion being met is measured on the basis of the likelihood of occurrence of four conditional variables. Thus, the resilience probability can be computed from the joint probability function of the four random variables. Since the four random variables are assumed to be independent, the probabilities of the four random variables are combined using their respective weights to compute the probability of resilience for a given node.

With all the information regarding the random variables of the TNR probabilistic model given (**Figure C4 [A]**), it is now possible to represent the problem as a network (**Figure C4 [B]**). Using the TNR probabilistic model, the total resilience probability of any certain node (firm) for any size can be found.

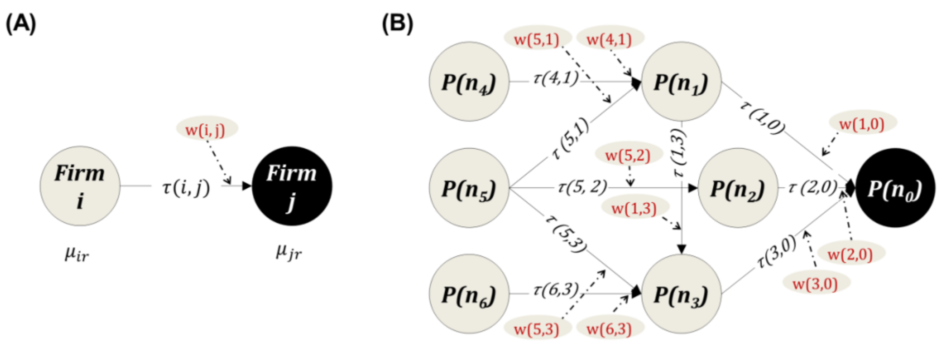


Figure C4. A conceptual example TNR probabilistic model

5.3.2 A TNR probabilistic model - An illustration case

Let us now illustrate the TNR probabilistic model. Based on a case example of six suppliers-one buyer network of manufacturing firms depicted in **Figure C4 (B)**, we assume that resilience requirements for the firms in the SC and relationship weight values are available, as shown in **Table C3** and **Table C4,** respectively.

Table C3. Initial information on the requirements of four attributes for firms

	Flexibility (φ_{i1})	Agility (φ_{i2})	Efficiency (φ_{i3})	Alertness (φ_{i4})
weights (k)	0.25	0.25	0.25	0.25
n_1	4.00	3.00	7.00	6.00
n_2	5.00	4.00	4.00	3.00
n_3	4.00	4.00	7.00	3.00
n_4	4.00	3.00	7.00	7.00
n_5	3.00	3.00	4.00	7.00
n_6	5.00	2.00	6.00	6.00

Table C4. Overview of relationship weight values among firms

Transacting firms	Weight value $w(i,j)$
(n_1,n_0)	0.50
(n_2,n_0)	0.25
(n_3,n_0)	0.25
(n_4,n_1)	0.28
(n_5,n_1)	0.72
(n_5,n_2)	1.00
(n_1,n_3)	0.22
(n_5,n_3)	0.33
(n_6,n_3)	0.45

Based on the assumption that the four criteria (flexibility, agility, efficiency, and alertness) are measurable and follow probability functions, we can compute their respective probabilities when the probability distributions are known. For example, the flexibility of Firm n_1 is expected to be resilient (likelihood of surviving when disruption occurs) if it is less than or equal to 4.00. Since we have assumed flexibility as a random variable, the probability of n_1's resilience in flexibility can be computed from its probability distribution.

For illustration, we utilize data we collected by surveying 298 SC experts from 10 different industries in Korea, in order to transform the initial deterministic model into a probabilistic model. The four normal probability functions for the four attributes are graphically shown in **Figure C5.**

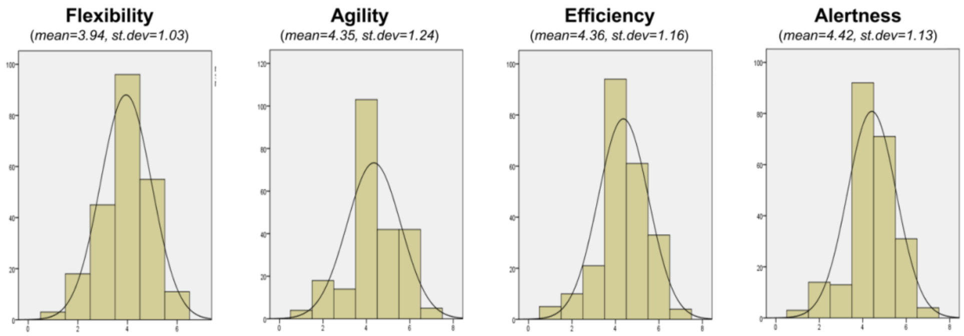


Figure C5. SC capabilities in probabilistic normal distribution (flexibility, agility, efficiency, alertness)

In **Table C5**, all the probability values used for this illustration are shown. With the probability values shown in the table, it is now possible to present a probabilistic model for the TNR model.

Table C5. Initial information of firms in probabilistic perspective

	Flexibility (μ_{i1})	Agility (μ_{i2})	Efficiency (μ_{i3})	Alertness (μ_{i4})	Weighted probability
weights (k)	*0.250*	*0.250*	*0.250*	*0.250*	-
n_1	0.523	0.139	0.989	0.920	0.643
n_2	0.848	0.390	0.377	0.104	0.430
n_3	0.523	0.390	0.989	0.104	0.502
n_4	0.523	0.139	0.989	0.989	0.660
n_5	0.181	0.139	0.377	0.989	0.422
n_6	0.848	0.029	0.921	0.920	0.680

Based on the empirical data, a normal probability distribution is formed for each criterion, and thus, we can express the probability that node n_i is true for resilience attribute μ with the value φ:

$$P(n_i) = survival\ likelihood\ of\ node\ n_i\ in\ case\ of\ a\ disruption$$
$$= \sum k_{ir}\, Pr(\mu_{ir} \leq \varphi_{ir}) \quad \forall i$$

Since the resilience of node is measured using the four SC capabilities and their assigned weights (k), we can then estimate the likelihood of firm n_1's resilience performance as follows:

$$P(n_1) = survival\ likelihood\ of\ node\ n_1\ in\ case\ of\ disruption$$
$$= k_{11}P(\mu_{11}) + k_{12}P(\mu_{12}) + k_{13}P(\mu_{13}) + k_{14}P(\mu_{14})$$
$$= 0.25Pr(\mu_{11} \leq 4.0) + 0.25Pr(\mu_{12} \leq 3.0) + 0.25Pr(\mu_{13} \leq 7.0) + 0.25Pr(\mu_{14} \leq 6.0)$$
$$= 0.25(0.523) + 0.25(0.139) + 0.25(0.989) + 0.25(0.920)$$
$$= 0.643$$

Let us also assume that SLMX values are Boolean random variables as depicted in **Table C6**. We operationalize SLMX as a conditional variable that enables the supplier to deliver as per its maximum capacity, based on the existing SC capabilities. For example, Firm n_4's flexibility capability of 4.00 is likely to be delivered to Firm n_1 with a probability of 0.28 and n_1's agility capability of 3.00 is likely to be delivered to the focal firm, n_0, with a probability of 0.50. Consequently, the focal firm's capabilities will be based on the capabilities of all its suppliers, which are conditional on the characteristic of the relationships.

Table C6. Summary of SLMX among firms

Exchange relationship SLMX, τ where $0 \leq \tau \leq 1$	
$(n_4, n_1) = 0.70$	$(n_1, n_3) = 0.80$
$(n_5, n_1) = 0.80$	$(n_1, n_0) = 0.30$
$(n_5, n_2) = 0.90$	$(n_2, n_0) = 0.70$
$(n_5, n_3) = 0.80$	$(n_3, n_0) = 0.90$
$(n_6, n_3) = 0.40$	

Using the probability values for both resilience and SLMX, the probability of the focal firm's total resilience level can be computed by aggregating the probabilities of all possible paths toward the focal firm. The computation formula is illustrated below:

$$\text{P(Focal Firm}, n_0)$$
$$= survival\ likelihood\ of\ focal\ firm, node\ n_0, in\ case\ of\ disruption$$

$$= \sum_{i=1} w(i,n_0)\tau(i,n_0)P(i)$$

$$= w(1,0)\tau(1,0)\{P(N_1) \times w(4,1)\tau(4,1)P(N_4)$$
$$+P(N_1) \times w(5,1)\tau(5,1)P(N_5)\}$$
$$+ w(2,0)\tau(2,0)\{P(N_2) \times w(5,2)\tau(5,2)P(N_5)\}$$
$$+ w(3,0)\tau(3,0)\{P(N_3) \times \mathrm{w}(1,3)\tau(1,3)P(N_1) \times \{\mathrm{w}(4,1)\tau(4,1)\mathrm{P}(N_4)$$
$$+ w(5,1)\tau(5,1)P(N_5)\}$$
$$+ P(N_3) \times \mathrm{w}(5,3)\tau(5,3)\mathrm{P}(N_5)$$
$$+ P(N_3) \times \mathrm{w}(6,3)\tau(6,3)\mathrm{P}(N_6)\}$$

When both the resilience random variables and the SLMX values are available, the TNR probabilistic model can be explicitly presented, as shown in **Figure C6**.

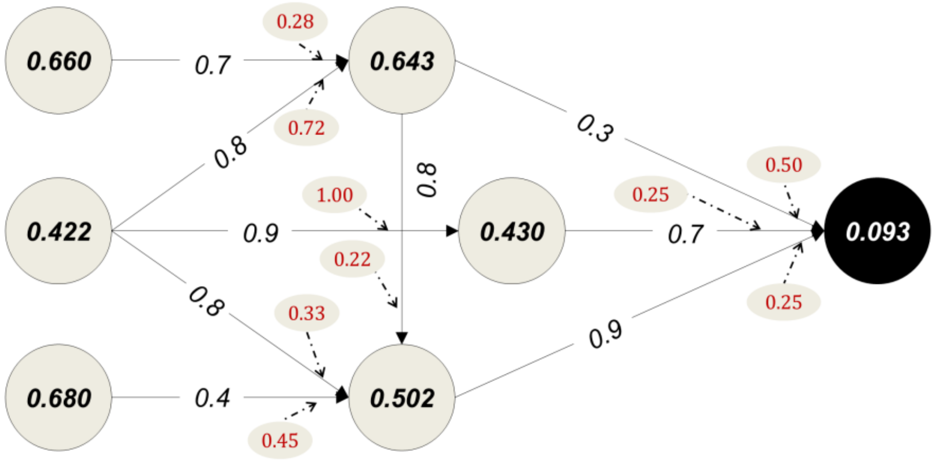


Figure C6. A TNR probabilistic model for illustration

5.3.3 Sensitivity analysis - SLMX

In this section, we perform sensitivity analysis in order to observe and understand the effect of changes in relationship behavioral uncertainty in the SLMX context on the focal firm’s overall network resilience performance. We do this with the help of an illustrative case example, as shown in **Figure C7** below. This step is particularly important since the degree of performance change can be effectively utilized to improve managerial understanding of the importance of SLMX. Moreover, this analysis can validate the feasibility of the proposed model because the model performance reacts reasonably to parameter changes.

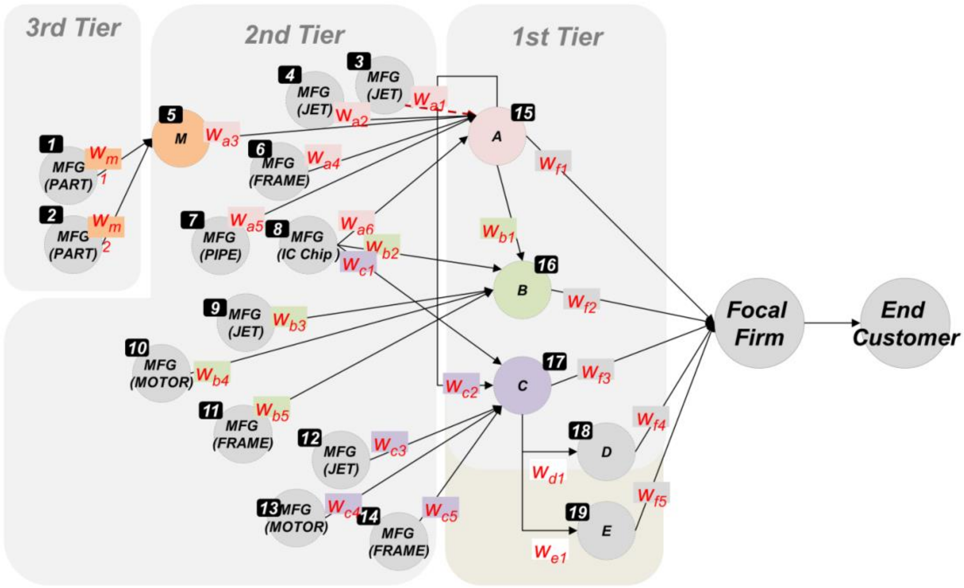


Figure C7. Example case

This study initially developed the model based on the assumption that SLMX follows a binary probability distribution between 0 and 1, where 0 represents the worst level of SN members. As depicted in **Figure C8**, it appears that the network resilience performance does not dramatically increase until the overall SLMX level reaches 0.6. On the other hand, given the existing SLMX parametric setting, the network can experience dramatic overall improvement even if overall SLMX is improved by as little as 25%. However, once the SLMX improvement percentage goes beyond 70%, the performance hardly increases.

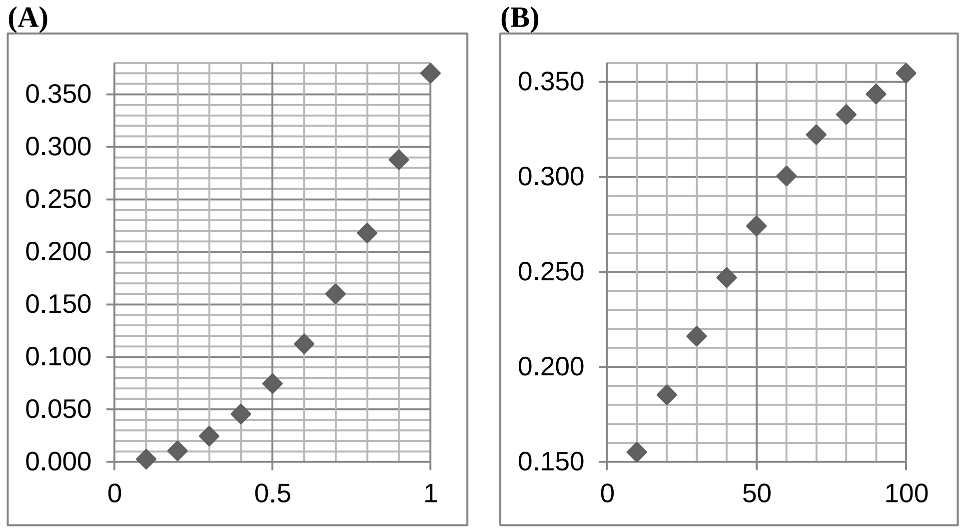


Figure C8. Level of TNR performance (y-axis) based on (A) SLMX variation and (B) SLMX enhancement % variation (x-axis)

Tier-level strategies

In previous analysis, we observed how the focal firm's perspective and strategic involvement in overall SLMX-level management at the network level may affect TNR performance. We consider a case where the focal firm may treat firms according to their tier level. For example, depending on the industry or market requirement, raw materials may be scarce and the network would rely heavily on the availability of downstream suppliers. In this case, the focal firm should make direct or indirect efforts to enforce a high level of commitment from the key suppliers to avoid vulnerabilities in the network.

In order to analyze the changes that may arise based on tier-level management approaches, we investigate five different SLMX management scenarios (**Table C7**):

1. Closely connected firms oriented management (decreasing) which focal firm heavily invests in maintaining a high-quality relationship with directly connected firms such as its 1st-tier suppliers, rather than with indirectly connected, 3rd-tier firms
2. Upstream suppliers oriented management (increasing), wherein focal firm requires a direct connection to maintain a high-quality relationship with the upstream suppliers

3. Immediate firms and suppliers oriented management (V-shape), in which focal firm requires high-quality relationships with both directly connected firms and upstream suppliers, while placing less emphasis on its relationship with the brokers
4. Logistics and assembler oriented management (inverted V-shape), in which the focal firm requires a strong commitment from the facilitators who play a more significant role that the other partner firms in the network
5. Standard management (uniform), wherein focal firm treats all relationships as equally important and requires a standardized relationship level from all firms

Depending on focal firm's perspective and involvement in managing overall network SLMX level, tier-level relationships may be affected. For instance, the focal firm may encourage or require directly connected firms to maintain a certain level of SLMX. Based on focal firm's (the SN leader) design of network relationship, TNR performance is expected vary, as shown in **Figure C9**.

Table C7. Cases of tier-level strategies (example of SLMX = 0.2 and 0.9)

	1st	**2nd**	**3rd**	**Avg.**
SLMX = 0.2				
1.Decreasing	0.40	0.15	0.05	0.20
2.Increasing	0.05	0.15	0.40	0.20
3.BrokerL (V-shape)	0.28	0.05	0.28	0.20
4.BrokerH (inverted V-shape)	0.10	0.40	0.10	0.20
5.Uniform	0.20	0.20	0.20	0.20
SLMX = 0.9				
1.Decreasing	1.00	0.90	0.80	0.90
2.Increasing	0.80	0.90	1.00	0.90
3.BrokerL (V-shape)	0.95	0.80	0.95	0.90
4.BrokerH (inverted V-shape)	0.85	1.00	0.85	0.90
5.Uniform	0.90	0.90	0.90	0.90

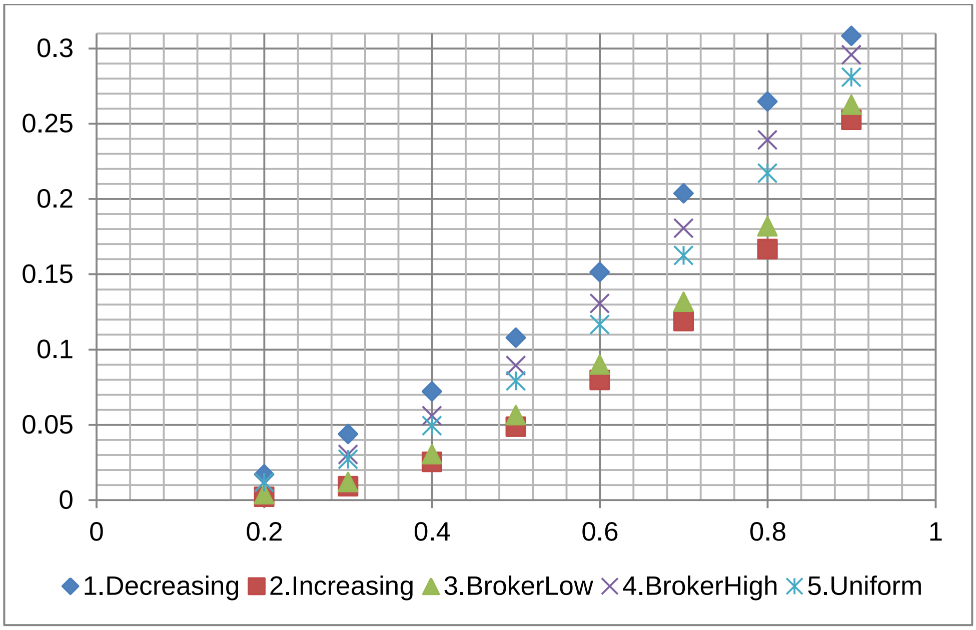


Figure C9. Gap variation among TNR performance levels (y-axis) based on the overall LMX level (x-axis) by the tier-level strategy

SLMX threshold tolerance testing

While we previously considered SLMX as a probabilistic variable that ranges between 0 and 1, in practice firms may have a relationship that is either perfectly positive (SLMX=1) or negative (SLMX=0). Firms may have a threshold level of relationship which dictates the firm's willingness to support the SC leader in case of disruptive events. In order to account for such a relationship, we can treat SLMX as a binary variable, taking either 1 or 0 as its value, based on a firm's perspective on the range of positive relationships, as shown in **Figure C10**.

If the firm's perceived threshold for a relationship to depict a perfectly positive commitment and loyalty is 0.5, the expected TNR performance level could be as high as 0.350. However, if the firm sets a high standard (such as 0.7) for a relationship to be considered extremely positive, then the TNR performance level could be viewed as low (below 0.050). Depending on the tolerance level for SLMX threshold, the overall network resilience performance will vary significantly.

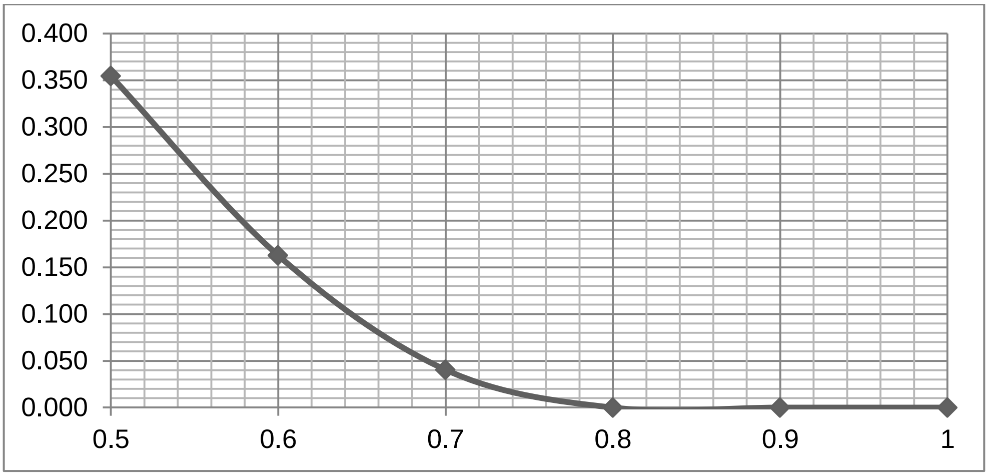


Figure C10. TNR performance (y-axis) changes based on the tolerance level of SLMX (x-axis)

The firms may decide on the threshold level, depending on the types of disruptive events and their frequency of occurrence. For example, if the suppliers, assemblers, or logistics service providers are minimally exposed to situations where they have to decide which firms to support in case of emergency, the high level of SLMX may only result in excessive investment in relationship management. However, if the network is constantly exposed to extraordinary events and requires frequent nonbinding favors from suppliers, the focal firm may need to maintain a uniquely high level of SLMX to gain a better market positioning than its competitors.

5.3.4 Sensitivity analysis - Network

In this section, we investigate how resilience performance changes among different network structure designs. We take the simplistic forms of network structures, as shown in **Figure C11** and **Table C8**, to compare the performance of the focal firm.

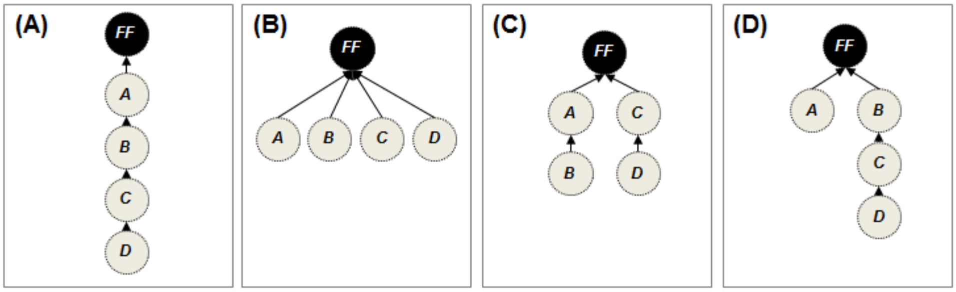


Figure C11. Investigated network structures

The four structure types are: (A) series; (B) horizontal; (C) mixed; and (D) complex, and their characteristics are described in **Table C8**. For example, the series model represents a strict hierarchical relationship among suppliers and buyers, which leads to a single final product and/or service. We compare the four design types based on resilience performance, while keeping both resilience and SLMX for each scenario identical. (It is to be noted that we demonstrate using computed values to maintain consistency with the thesis; however, an explicit computation formula for each of the four network types would be better.)

Table C8. Description of network structure design

Structure design	Structure characteristics
(A) Series	Strict hierarchical relationships among suppliers and buyers which lead to single final product and/or service
(B) Horizontal	Equally contributes to single final product and/or service
(C) Mixed	Both hierarchical and uniform relationships form network structure and displays group (cluster) driven movement
(D) Complex	Both hierarchical and uniform relationships form network structure, but displays unidentified cluster preferences or formation

Figure C12 depicts resilience performance by varying SLMX and SC capability level (left) and graphical representation of it (right). In a series structure design

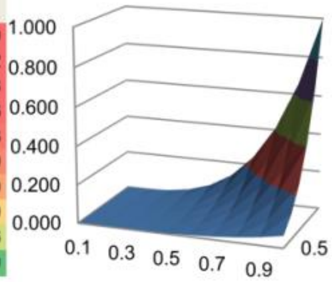
(**Figure C12 [A]**), the level of SLMX does not appear to affect overall resilience performance at all when the existing SC capability is significantly low, that is, 0.7. The significant role of SLMX becomes apparent as the resilience performance improves from 43.0% to 65.6% and from 65.6% to 100% when the existing SC capability is set as 0.9 and 1, respectively.

In a horizontal network structure design (**Figure C12 [B]**), SLMX is as important as the SC capability. If the level of SLMX is below the level of SC capability, the drop in resilience performance is proportionate to the decrease in SLMX value. Moreover, without a stable SLMX value, resilience performance may remain low, even with a high level of SC capability. For example, when SC capability is as high as 0.9, and SLMX is below 0.5, resilience performance is expected to fall below 50%.

In the comparison between mixed (**Figure C12 [C]**) and complex (**Figure C12 [D]**) structure, the former is found to display a relatively higher resilience performance. The level of SLMX appears to have a higher effect on resilience performance in case of the complex structure, where only a single firm forms an in-depth hierarchical structure (compared to two firms forming an equally low hierarchical structure). However, the resilience performance of these structures remained below that of the horizontal structure.

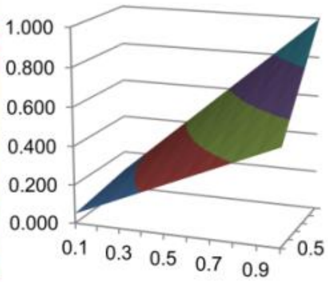
(A) Series

LMX	SC Capability 0.5	0.6	0.7	0.8	0.9	1
0.1	0.000	0.000	0.000	0.000	0.000	0.000
0.2	0.000	0.000	0.000	0.001	0.001	0.002
0.3	0.001	0.001	0.002	0.003	0.005	0.008
0.4	0.001	0.003	0.006	0.010	0.017	0.026
0.5	0.004	0.008	0.015	0.026	0.041	0.063
0.6	0.008	0.017	0.031	0.053	0.085	0.130
0.7	0.015	0.031	0.058	0.098	0.158	0.240
0.8	0.026	0.053	0.098	0.168	0.269	0.410
0.9	0.041	0.085	0.158	0.269	0.430	0.656
1	0.063	0.130	0.240	0.410	0.656	1.000



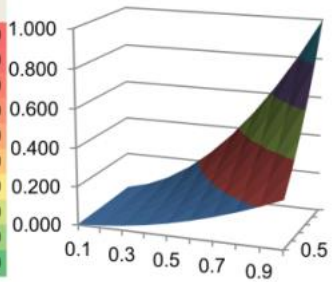
(B) Horizontal

LMX	SC Capability 0.5	0.6	0.7	0.8	0.9	1
0.1	0.050	0.060	0.070	0.080	0.090	0.100
0.2	0.100	0.120	0.140	0.160	0.180	0.200
0.3	0.150	0.180	0.210	0.240	0.270	0.300
0.4	0.200	0.240	0.280	0.320	0.360	0.400
0.5	0.250	0.300	0.350	0.400	0.450	0.500
0.6	0.300	0.360	0.420	0.480	0.540	0.600
0.7	0.350	0.420	0.490	0.560	0.630	0.700
0.8	0.400	0.480	0.560	0.640	0.720	0.800
0.9	0.450	0.540	0.630	0.720	0.810	0.900
1	0.500	0.600	0.700	0.800	0.900	1.000



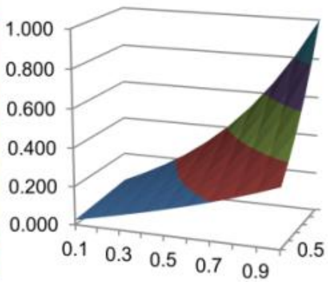
(C) Mixed

LMX	SC Capability 0.5	0.6	0.7	0.8	0.9	1
0.1	0.003	0.004	0.005	0.006	0.008	0.010
0.2	0.010	0.014	0.020	0.026	0.032	0.040
0.3	0.023	0.032	0.044	0.058	0.073	0.090
0.4	0.040	0.058	0.078	0.102	0.130	0.160
0.5	0.063	0.090	0.123	0.160	0.203	0.250
0.6	0.090	0.130	0.176	0.230	0.292	0.360
0.7	0.123	0.176	0.240	0.314	0.397	0.490
0.8	0.160	0.230	0.314	0.410	0.518	0.640
0.9	0.203	0.292	0.397	0.518	0.656	0.810
1	0.250	0.360	0.490	0.640	0.810	1.000



(D) Complex

LMX	SC Capability 0.5	0.6	0.7	0.8	0.9	1
0.1	0.025	0.030	0.035	0.040	0.045	0.051
0.2	0.051	0.061	0.071	0.082	0.093	0.104
0.3	0.077	0.093	0.110	0.127	0.145	0.164
0.4	0.104	0.127	0.151	0.176	0.203	0.232
0.5	0.133	0.164	0.196	0.232	0.271	0.313
0.6	0.164	0.203	0.247	0.295	0.349	0.408
0.7	0.196	0.247	0.304	0.368	0.440	0.522
0.8	0.232	0.295	0.368	0.451	0.547	0.656
0.9	0.271	0.349	0.440	0.547	0.671	0.815
1	0.313	0.408	0.522	0.656	0.815	1.000



0.001 0.500 1.000

0.000-0.200 0.200-0.400 0.400-0.600 0.600-0.800 0.800-1.000

Figure C12. Results of network resilience performance (y-axis) dependent on LMX value (x-axis) given SC capabilities (z-axis)

5.4 Discussion

5.4.1 Bayesian modeling based approach

As we have exemplified how TNR model can be interpreted as a probabilistic model utilizing survey data in previous section, we now explore other means to generalize the TNR model by utilizing actual observable data. SC capabilities are not just measurable through cardinal or ordinal evaluation by the experts; they can also be measured by using historical data on actual operations. For example, we construct node variables with conditional probabilities that are related to operational uncertainties, and link variables with suppliers' behavioral uncertainties as follows:

Operational uncertainty:

$$\mathrm{P}(n_i) = \Pr(\mu_{ir} \leq required\ performance) \qquad \forall i$$

Behavioral uncertainty:

$$\mathrm{P}(\tau_i) = \Pr(\tau_{ir} = true) \qquad \forall i$$

More specifically, these are prior variables that are dependent on posterior variables. We show how conditional variables may be formed (also known as the node probability table) by adopting an approach similar to that of Hosseini and Barker (2016). To demonstrate how Bayesian approach can be adopted in evaluating overall resilience, we provide an example of a firm's resilience assessment based on its flexibility attribute in **Table C9** (*directly adopted from Hosseini and Barker (2016)).

Table C9. Node probability table of flexibility capability

Variable name	Node probability table	Implication
1. Supply flexibility		
A. Delivery robustness*	*IF (lead time < 17 and response rate > 0.9, "True", "False")*	If the lead time is less than 17 days and response rate is greater than 90%, then the supplier's delivery is referred robust
(1) Lead time*	*TNORM (μ = 15, σ^2 = 1.5, LB = 1, UB = 21)*	Supplier takes an average of 15 days to deliver requested product to the buyer
(2) Response rate*	*TNORM (μ= 0.94, σ^2= 0.0001, LB = 0.87, UB = 1)*	Supplier is able to respond to requests 94% of the time
B. Surplus inventory*	*True = 90%, False = 10%*	90% of the time the supplier keeps surplus inventory
2. Product-related flexibility		
A. Product mix	*IF (accommodation level of minor design changes > 0.80 and accommodation level of new product design changes > 0.50, "True", "False")*	If the accommodation level of minor design changes is above 70% and the accommodation level of new product design changes is above 50%, the product mix flexibility is said to be True, otherwise False
(1) Accommodation level of minor design changes	*TNORM (0.875, 0.005, 0.75, 1)*	Supplier is able to accommodate for minor design changes 70% of the time
(2) Accommodation level of changes for new product design	*TNORM (0.6, 0.005, 0.40, 0.80)*	Supplier is able to accommodate for new product design changes 30% of the time
B. Product quality*	*True = 90%, False = 10%*	if the probability of supplier not conforming to specification is less than 7%, then the quality of product is acceptable (True), otherwise false
(1) Probability product is faulty*	*True = 90%, False = 10%*	The probability of a defected product being delivered follows a beta distribution

Table C9. Node probability table of flexibility capability (cont.)

Variable name	Node probability table	Implication
3. Process-related flexibility		
A. Production process stability	*IF (probability of production fluctuation < 15%, true, false)*	If the probability of production fluctuation is less than 20%, production process stability is said to be True, otherwise False.
(1) Production fluctuation	*TNORM (0.10, 0.005, 0.05, 0.20)*	Production output fluctuates on average of 10% of the time
B. Alternative manufacturers	*IF (alternative production site availability > 0.9, "True", "False")*	The availability of alternative manufacturers is True if the likelihood exceeds 95%
(1) Alternative production site availability	TNORM (0.80, 0.005, 0.95, 1)	Alternative production sites are available for unplanned production request on average of 80% of the time

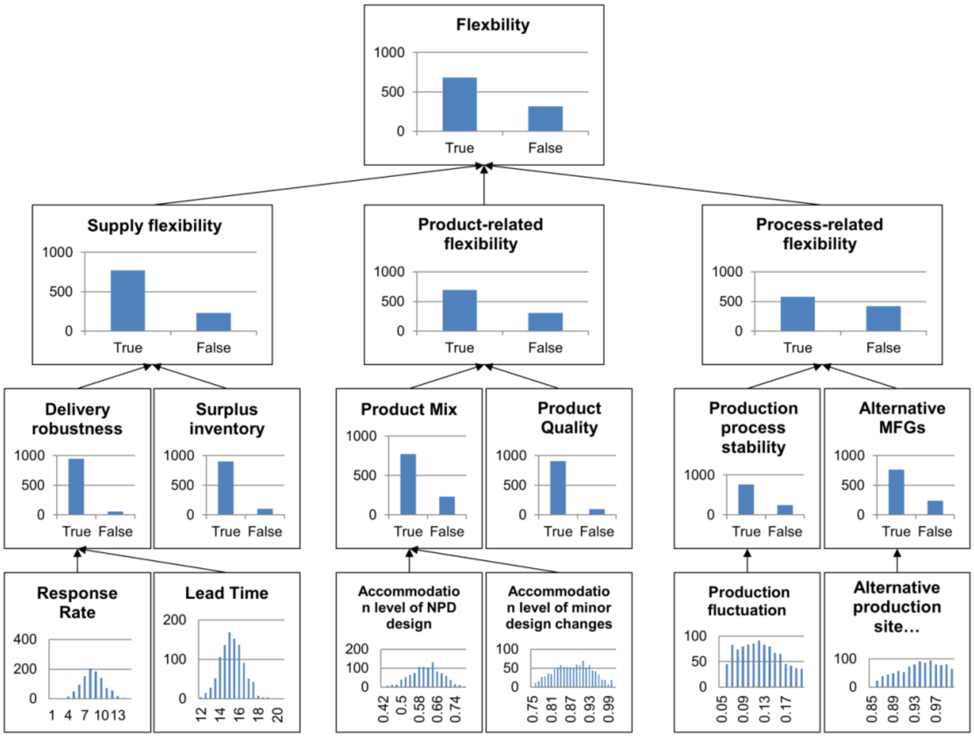


Figure C13. The BN model of firm's flexibility performance

The result of the Bayesian network analysis is shown in **Figure C13**. The likelihood of flexibility capability meeting the requirement is shown at the top of the figure and such approach can be applied to other SC capabilities of interest to measure overall network resilience based on observed field data. Therefore, we claim that the proposed TNR probabilistic model can be generalized for the situation where field data is practically available.

5.4.2 Critical path based approach

From a managerial perspective, the identification process of key paths that expose network to vulnerability may be critical to resilience management. Thus, based on the identified resilience value for each path, we can visualize overall network resilience status, with the critical paths identified, as shown in **Figure C14** and **Figure C15**. Similarly, paths that are considered to be either under- or over-managed partnerships are also vital to efficient management as such an effort requires financial investment and time. In **Figure C15**, we divide the situation into four areas to illustrate the criticality of SC resilience paths. Other variations would be feasible for improving the validity of the proposed mode. Generally speaking, it is clear that the graphical representation makes possible most traditional network studies, such as critical path, bottleneck, and economic analysis, which may be conducted for further elaboration of the TNR probabilistic model.

Path	Total R
wf1	0.143
wf2	0.083
wf3	0.051
wf4	0.107
wf5	0.034
wa1	0.009
wa2	0.010
wa3	0.005
wa4	0.011
wa5	0.007
wa6	0.014
wb1	0.004
wb2	0.011
wb3	0.003
wb4	0.007
wb5	0.006
wc1	0.004
wc2	0.002
wc3	0.003
wc4	0.004
wc5	0.003
wd1	0.016
we1	0.003
wm1	0.015
wm2	0.003

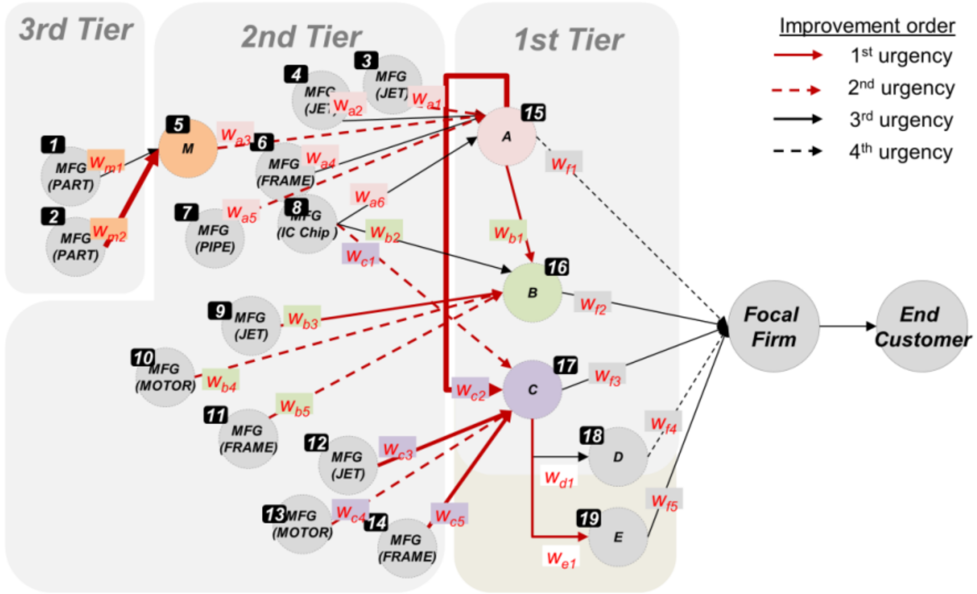


Figure C14. Visualized critical paths that require improvement for TNR performance improvement

Path	R	SLMX	Path	R	SLMX
wf1	High	Low	wb2	High	High
wf2	High	Low	wb3	Low	Low
wf3	High	Low	wb4	Low	Low
wf4	High	Low	wb5	Low	Low
wf5	High	Low	wc1	Low	Low
wa1	High	High	wc2	Low	Low
wa2	High	High	wc3	Low	Low
wa3	Low	Low	wc4	Low	Low
wa4	High	Low	wc5	Low	High
wa5	Low	Low	wd1	High	High
wa6	High	Low	we1	Low	Low
wb1	Low	Low	wm1	High	High
			wm2	Low	High

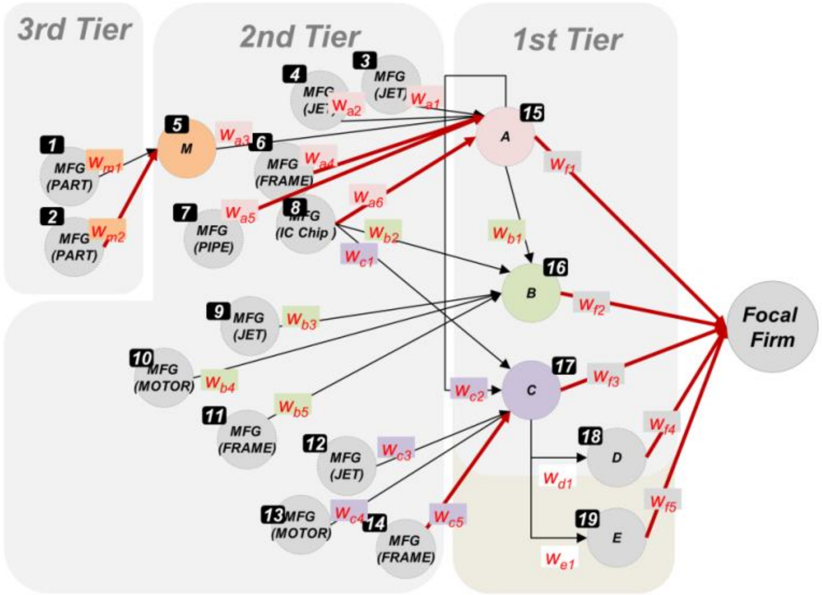


Figure C15. Visualized critical paths that are either under- or over-managed from the efficient management perspective

5.5 Conclusion, implication and limitations

This study proposes both deterministic and probabilistic modeling approaches for measuring TNR performance. Here we explained the underlying concept behind the model and explained the approach and implementation process by using the case study of a global manufacturing company based in Korea. Some variations of the model have been also delineated for further generalization in the future. Besides, the impact of SLMX on resilience performance has been investigated in depth to improve the applicability of the proposed model.

From a theoretical perspective, the integrative exchange relationship theory and social network theory offers a holistic view of the network resilience model. LMX theory not only enables the quantitative representation of interrelationships among firms, but also complements the resource based view in understanding TNR performance.

From a managerial perspective, the firm or its existing market may be naturally exposed to certain types of risks, such as those related to demand, supply, or even logistics. Thus, the appropriate tier-level SLMX management can be applied to mitigate the overall consequences, as shown in **Table C10**. When preparing for the three types of risks proposed by Wagner and Bode (2006), the focal firm can proactively decide on how to allocate limited time and resources for each tier.

Table C10. Examples of feasible tier-level SLMX strategy for various risk types

Types of risks	Network characteristics	Feasible tier-level LMX strategy to mitigate vulnerabilities
Demand side risk		
- Unanticipated or very volatile demand - Insufficient or distorted information customers about orders	▪ Relies on directly connected firms to carry sufficient inventory level at all times to meet immediate requests of products and services	▪ Direct connected firms oriented management (decreasing from 1st to last tier)
Supply side risks		
- Poor logistics performance of suppliers - Supplier quality problems - Supplier bankruptcy	▪ Relies on upstream suppliers to have steady quality of products and a stable financial standing	▪ Upstream suppliers oriented management (increasing from 1st to last tier)
Supply/Logistics side risks		
- Poor logistics performance of logistics service providers - Capacity fluctuations or shortages on the supply markets	▪ Relies on middle tier-level firms (brokers, assemblers, or logistics providers) to have various means to deliver fulfillments and enable continuous material flow	▪ Logistics and assembler oriented management (inverted V-shape)
Catastrophic risks		
- Political instability, war, civil unrest, or other socio-path crises - International terror attacks - Disease or epidemics - Natural disaster	▪ Relies on all tier-level firms to be able to support focal firm in case of any disruptive events	▪ Standard management (uniform)

While the study fulfills the objective in demonstrating approaches to measure network resilience, there are several areas on which future studies can focus. First, the analysis is limited to a case study of a single firm in Korea. Therefore, the result of the analyses cannot be generalized and can only provide a generic guideline in how to utilize the proposed model. Thus, the validity of the model may be further investigated through additional investigations of other firms that are in acute need of resilience performance improvement.

Second, it is important to note that this extension is contingent on all firms following convergence theory based on a cross-national theoretical perspective. LMX is fundamentally driven from an individual analysis and in the process of reconciling the potential issue of integrating SLMX in a firm- or network-level, convergence theory is utilized. Among three characteristics of cultural status (convergence, divergence, crossvergence), we base our analysis on the assumption that the societal or managerial values of each firm’s managers or decision makers will be aligned with those of the firm (Sharif & Irani, 2012). It would be meaningful to extend this study to investigate relational behavior based on divergence (where individual’s values will dictate firm’s values) or crossvergence (where the firm’s values are a joint output of the individual’s and firm’s traditional values) for a more comprehensive analysis.

Third, an in-depth network structural analysis can be performed utilizing the TNR model proposed by us. We expect such an analysis, which considers triadic relationships and diverse network structural properties, to lead to meaningful findings about optimal resilience management in terms of time and financial tradeoffs.

CHAPTER 6

CONLCLUSION

6.1 Theoretical implications

The primary objectives of this study are: (1) to determine the critical attributes for SC resilience; (2) to present a network-based structure for managing the levels of resilience; and (3) to propose a comprehensive network resilience model for both deterministic and probabilistic situations.

This thesis first elicits important resilience attributes, among which a number of determinant attributes are critical for SCM sustainability. The resilience capabilities introduced in the existing literature are systematically investigated and classified, based on a value hierarchy. A survey study is then conducted in order to validate the important exchange relationship attributes and SC capabilities. Second, a graphical representation is proposed to visualize the resilience relationship in a network formation. A node here represents a partner firm’s resilience capability in the supply network and the network value consists of the positional value of the firm. We then adopt an outranking methodology, CDA, to provide a process to identify the improvement priority order. Finally, a TNR model is proposed to handle resilience levels and interrelationships of the firms simultaneously. The proposed model is also extended to serve as a probabilistic model, along with a number of sensitivity studies, to improve its applicability.

The study may contribute theoretically to the literature as follows:

First, this thesis isolated four key determinant attributes of SC resilience through a comprehensive analysis of existing capabilities. The impact of the four attributes on resilience has been verified with a survey study.

Second, the interrelationships of the firms have been expressed using LMX. Through the survey analysis, it was found that LMX affects SC resilience significantly.

Third, a BNR model using resilience and network value has been proposed, along with an ordering approach. The network representation visualizes not only all the levels of resilience of the firms but also their influences within the network structure.

Fourth, a TNR model is developed, through which one can handle both resilience and interrelations among the firms. The model is applicable to both deterministic and probabilistic cases.

With a further effort on elaboration, we believe that the research results may prove to be a solid basis for network-based research in the area of SCM.

6.2 Managerial implications

The thesis has primarily focused on providing a practical tool visually represent the structure of resilience for the practitioners.

With regards to exchange relationship driven SC capabilities – SC resilience model, it is vital to understand that optimal SC performance is achievable only through a collaborative effort. Specifically, in the context of post-disruption, high perceived level of trust, respect, and obligation among the firms is necessary in order to collectively experience resilient performance.

With regards to the applicability and usefulness of bicriterion network resilience model, the suggested model can not only objectively assess the performance and risk exposure level of firms, but it can also effectively aid in identifying firms with balanced capabilities for feasible amount of exposure to vulnerability or firms with unbalanced capabilities for high exposure to vulnerability.

With regards to the applicability and usefulness of total network resilience model, the firm or its existing market may be naturally exposed to certain type of risk such as demand, supply, or even logistics. Thus, the appropriate tier-level LMX management can be applied to mitigate the overall consequences of demand-, supply side-, and supply/logistics-side risks. In preparation for three types of risks proposed by Wagner and Bode (2006), focal firm can proactively decide in how to allocate limited time and resources by each tier.

6.3 Research limitation and future research

This thesis has focused on proposing a comprehensive network model for SC resilience. **Table X1** lists overall relevant questions that are addressed (1st and 2nd level of studies) in the current study, and highlights future avenues (3rd and 4th level of studies)

Table X1. Overview of relevant questions for each level of studies (*future avenues)

Level of studies	1st Conceptual Empirical	2nd Managerial	3rd Optimization*	4th Theoretical*
Classifications	*System phases (Anticipate / Adapt / Respond / Recover / Grow)*	*Managerial application and implication*	*Optimization modeling, simulation modeling, and economic modeling*	*Theory development and validation*
Supply-perspective	• What are the key determinants of SC resilience performance?	• How can firm managers assess resilience performance?	• How to efficiently manage capabilities for optimal resilience performance?	
Network-perspective	• How does supply network members' level of resilience capability affect overall network resilience performance?	• How can firm managers manage its complex network for overall resilience performance?	• What is the optimal network structural design for resilience performance?	
Relational-perspective	• How does interrelationship value affect resilience performance?	• What is a contingent relational aspect in managing the supply network resilience model?	• What is the optimal relationship value management policy for a cost effective resilience performance?	

The following issues must be further developed to make the research findings:

With regards to exchange relationship driven SC capabilities – SC resilience model, future research may further investigate our findings from both theoretical and empirical approaches. First, future research could theoretically propose how different level of exchange relationship may affect different types of SC capabilities in different contexts such as innovation versus merely a common product focused supply chain relationship. Second, we encourage future studies to theorize and empirically confirm how perceived exchange relationship from both firms (buying firm and supplying firm) comprehensively affects the SC resilience performance. Finally, future studies are recommended to explore the causal relationships among SC capabilities and SC resilience based on different phases of disruptions (pre-, during-, and post-). Both academic researchers and practitioners could benefit from thorough understandings of system dynamics and performance behaviors in varying contexts.

With regards to generalizing bicriterion network resilience model, future studies are encouraged to investigate the following questions with regard to validity and generalizability of the model**:** (1) How closely can the BNR model predict actual practitioners' qualitative perspective? Is the priority assessment of network model expected to change dependent on industry type? It is important to adjust the model as accurate as to real-world perspective. (2) How do the values of network and resilience change as network structure changes? Dependent on industry or firm's strategy, design of network structure will vary. Thus, the validity of the model could be tested in varying network settings. (3) How would the resilience model change in different culture or exchange relationship contexts? We suggest future studies to include cultural or exchange relationship in the resilient management model. Hohenstein et al. (2015) noted that cultural specific research in global supply chain context can improve SC resilience strategies in varying national culture context. Modern supply chain calls for complex and global relationships, thus exchange relationship whether it is based on cultural difference or regional difference should be evaluated for further investigation.

With regards to contingent application of exchange relationship, it is important to note that this extension is contingent on that all firms follow convergence theory from cross-national theoretical perspective. LMX is fundamentally driven from an individual analysis and in the process of reconciling the potential issue of integrating SLMX in a firm- or network-level, convergence theory is utilized. Among three characteristics of cultural status (convergence, divergence, crossvergence), we base our analysis on the intuition that the each firm's managers or decision makers' societal or managerial value will emerge aligned with firm's direction (Sharif & Irani, 2012). It would be meaningful to extend this study to investigate relational behavior based on divergence (where individual's value will dictate firm's value) or crossvergence (where firm's value is in a form of combinatory output of individual and firm's traditional value) for more comprehensive analysis.

As for the in-depth network structural analysis, future studies are encouraged to utilize our proposed TNR model in considering triadic relationship and diverse network structural properties. Such efforts are expected to lead to meaningful findings for optimal resilience management in terms of time and financial tradeoffs.

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APPENDIX A1. Preliminary survey for key SCRES capability identification

A. <u>FIRM CHARACTERIZATION</u>

1. Number of employees
2. Primary product(s)
3. Primary customer activity(s)
4. Your job position
5. How do you define you firm's position in your supply chain? (focal firm, 1st tier, 2nd tier)

B. <u>SURVEY</u>

The questionnaire is designed to be reasonably quick to answer. Please mark in the relevant cell depending on your choice. Please provide you view of the influence of supply chain capabilities

Capabilities	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}
X_1 Flexibility														
X_2 Redundancy														
X_3 Velocity														
X_4 Visibility														
X_5 Collaboration														
X_6 Agility														
X_7 Robustness														
X_8 Efficiency														
X_9 Alertness														
X_{10} Tech. capability														
X_{11} Alignment														
X_{12} Cultural														
X_{13} Op. Competency														
X_{14} Information Sharing														

APPENDIX A2. Survey for measurement model

Construct		Measurement	Loadings
Flexibility (X_1) (Mandal et al., 2016)	X_{11}	*Adjust delivery time of supplier's order for mitigating a disruption*	0.90
	X_{12}	*Adjust production volume capacity in response to a disruption*	0.93
	X_{13}	*Adjust its delivery schedules for coping with disruptions*	0.89
Agility (X_2) (X. Li et al., 2017)	X_{21}	*Adapt supply chain processes to reduce lead time*	0.89
	X_{22}	*Adjust supply chain processes to increase on-time delivery*	0.91
	X_{23}	*Streamline supply chain processes to reduce non-value-added activities*	0.89
	X_{24}	*Adapt supply chain processes to reduce new product development cycle time*	0.90
Efficiency (X_3) (Gligor et al., 2015)	X_{31}	*Distribution costs (including transportation and handling costs)*	0.90
	X_{32}	*Manufacturing costs (including labor, maintenance, and re-work costs)*	0.91
	X_{33}	*Inventory costs (including inventory investment and obsolescence, work-in-progress, and finished goods)*	0.86
Alertness (X_4) (X. Li et al., 2017; T.J. Pettit et al., 2013)	X_{41}	*Track macroeconomic changes (i.e., structural shifts in markets caused by economic progress, political and social change, demographic trends, and technological advances)*	0.87
	X_{42}	*Detect threats to supply networks (closely monitor deviations to normal operations, including near misses)*	0.89
	X_{43}	*Detect sudden changes in demand (via demand forecasting method)*	0.89
	X_{44}	*Detect unexpected changes in the physical flow throughout the supply chains*	0.91
	X_{45}	*We have detailed contingency plans and regularly conduct preparedness exercises and readiness inspections*	0.91
Resilience (X_5) (Brandon-Jones et al., 2014)	X_{51}	*How well is your firm prepared for a disruptive event?*	0.89
	X_{52}	*After disruptive event, how well can your firm's material flow be quickly restored?*	0.92
	X_{53}	*After disruptive event, how fast can your firm deal with disruptions?*	0.86
	X_{54}	*After disruptive event, how easily can your firm recover normal operating performance?*	0.87
LMX (X_6) (Graen & Uhl-Bien, 1995)	X_{61}	*How well does your key buyer understand your job problems and needs?*	0.92
	X_{62}	*How well does your leader recognize your potential?*	0.88
	X_{63}	*How would you characterize your working relationship with your leader?*	0.92
	X_{64}	*How active would you characterize your firm's participation in the key buyer's leading supply network activities (i.e., regular workshop, forums, etc.)*	0.89

Abstract in Korean (국문초록)

공급네트워크 복원력을 위한 통합 모델: 역량, 교환 관계 및 네트워크 속성

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공급사슬관리 (SCM: Supply Chain Management) 활동과 성과는 비즈니스 프로세스의 갑작스러운 파괴적인 사건에 취약하다. 구체적으로 말하자면, 위기발생 시 공급망(SC: supply chain)이 경험하는 3 단계 (감각, 대응, 복구) 중에서 본 연구는 복구 활동에 초점을 맞추고 있다. 예컨대, 위기로 인해 공급 중단이 발생하면 기업은 시설을 이전하고 네트워크 역량 및 유연성을 활용하여 생산기능을 대체 또는 신규 공급 업체로 전환해야 한다. 이러한 복구 활동을 리질리언스 (resilience) 활동 또는 SC 리질리언스 라는 용어로 지칭한다. 본 논문의 주요 목적은 SC 리질리언스와 관련된 모든 중요한 속성들을 철저히 조사하고 네트워크 관점에서 여러 회사 간의 리질리언스 수준을 보여줄 수 있는 종합적인 방식을 제세하는 것이다. 본 논문은 SC 리질리언스 향상에 매우 중요한 이슈를 실질적으로 해결하기 위해서 다음과 같은 세 가지 과제를 순차적으로 다룬다: (1) SC 리질리언스에 대한 중요한 속성을 결정, (2) SC 리질리언스 수준을 관리하기 위한 네트워크 구조 제시, (3) 결정론적 (deterministic) 상황과 확률적 (probabilistic) 상황을 다룰 수 있는 종합적인 네트워크 리질리언스 모델 제시.

본 연구는 우선 중요한 리질리언스 속성을 도출한 후에 지속가능한 공급망 확보에 요구되는 핵심 속성을 찾아낸다. 기존 문헌에 소개된 리질리언스 역량들을 가치 계층 (value hierarchy)을 초점을 맞추어 체계적으로 조사 및 분류한다. 그 다음, 설문조사를 통해서 교환 관계 속성(exchange relationship)과 공급망 역량 (SC capabilities)을 검증한다. 둘째,

네트워크 관점에서 리질리언스 관계를 시각화할 수 있는 그래픽 표현을 제시한다. 여기서 마디(node) 가치는 공급 네트워크에 속한 협력업체들의 리질리언스 수준을 나타내며, 네트워크 가치는 협력업체들의 위치 및 연결성 수준을 나타낸다. 또한, 협력업체 리질이언스의 개선 우선순위를 도출하는 프로세스를 위해서 순위결정 방법인 '일치성과 불일치성 접근 방식 (CDA: Concordance and Discordance Approach)'을 적용한다. 마지막으로, 기업의 리질리언스 수준과 상호 관계를 동시에 처리 할 수 있는 토탈 네트워크 리질리언스 (total network resilience) 모델을 제시한다. 모델의 활용도를 높이기 위해서 확률론적 모델로 확장시키고 민감도 분석도 실시한다.

본 연구는 이론적으로 다음과 같이 문헌에 기여할 것으로 기대된다. 첫째, 기존 역량들에 대한 포괄적인 분석을 통해 SC 리질리언스의 네 가지 핵심 결정요소를 찾아내고 요소들의 영향력을 설문조사를 통하여 검증하였다. 둘째, 기업들간의 상호 관계를 리더-멤버 교환 이론 (LMX: Leader-Member Exchange theory)에 근거하여 정리했으며, LMX 또한 SC 리질리언스에 상당한 영향을 미치는 것을 확인하였다. 셋째, 리질리언스 및 네트워크 가치를 이용한 이중기준 네트워크 리질리언스 (BNR: Bicriterion network resilience) 모델을 우선순위 결정 방법과 함께 제시하였다. 기업들의 리질리언스 수준뿐만 아니라 네트워크 구조 내에서의 변화 및 영향들을 가시화 시켰다. 넷째, 공급 네트워크의 모든 회사들의 리질리언스 수준과 상호관계성을 관리 할 수 있는 TNR 모델을 개발하였다. 이 모델은 결정론적 및 확률적 상황에 모두 적용 할 수 있다.

SC 리질리언스에 공급망 역량, 교환 관계 및 네트워크 속성의 영향을 조사하면 향후 연구에 의미 있게 기여할 것이다. 공급망 관점에서 볼 때, 후속 연구에서는 위기발생 시 여러 가지 단계의 중단 (예: 사전, 중간 및 사후)을 기반으로 SC 역량과 SC 리질리언스간의 인과 관계를 조사할 수 있다. 또한, 보다 포괄적 인 분석을 위해 발산(divergence) 또는 교차점 (crossvergence)상황에 기반한 관계형 행동을 연구 할 수도 있다. TNR 모델을

이용하여 triadic 관계와 다양한 네트워크 구조 특성을 분석하는 것도 후속 연구로 고려될 수 있다. 본 연구 결과를 지속적으로 발전시키면 네트워크 기반 공급망관리 연구에 탄탄한 토대를 마련될 것으로 판단한다.

주요어 : 공급사슬관리, SC 리질리언스, SC 역량, SC 교환관계, 공급 네트워크, 공급 네트워크 리질리언스

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