applied sciences

MDPI

Article

Facilitating Vulnerable Supplier Network Management Using Bicriterion Network Resilience Management Approach

Nina Shin [1] and Sangwook Park [2,*]

1 School of Business, Sejong University, Seoul 05006, Korea; ninashin@sejong.ac.kr
2 School of Business, Seoul National University, Seoul 08826, Korea
* Correspondence: sangpark@snu.ac.kr

Received: 28 September 2020; Accepted: 25 November 2020; Published: 28 November 2020

Abstract: This study aims to enable a high level of coordination to cope with increasing levels of uncertainty by computing supplier- and network-based resilience values. Our case study is based on a real-world highly connected global manufacturing firm based in Korea as a test environment to evaluate a proposed bicriterion network resilience model using resilience and network values, together with an ordering approach. An outranking methodology is used to determine the improvement priorities of suppliers to achieve a high level of overall network resilience. The results show that the effectiveness of a firm's performance with respect to the entire supply chain may increase or decrease based on its embeddedness and connectivity within the supply network. This study is one of the first to provide an integrative (resilience capabilities and network attributes) approach to the supplier improvement model, future studies are encouraged to expand the model to different network settings.

Keywords: supply network resilience; sustainable production system; superiority–inferiority ranking; sustainability assessment visualization

1. Introduction

Supply chain (SC) resilience management dealing with supply, demand, logistics, and catastrophic disruptions takes a complex and mixed approach, such as capacity management [1,2], key SC resilience drivers management [3,4], network structure management [5–7], vulnerability management [8–10], and supplier management [11,12]. Particularly, the supply network that is experiencing successful globalization of economy enabled through rapid technology advancement may anticipate the impact of ripple effect of local disruption to be very long lasting and expensive [13]. Local instability in supply chain can trigger and amplify vulnerability across interconnected supply chain networks, resulting in a significant disruption of whole network [14]. In July 2019, when the Japanese government imposed a tougher restriction on exports, Samsung Electronics and SK Hynix had to scramble to find new suppliers of key materials for producing semiconductors and displays [15]. Samsung Electronics and SK Hynix lost approximately USD 13 billion and USD 1.2 billion market value, respectively, as those materials are essential for producing semiconductors which accounts for more than 70% of the global DRAM market and 40% of the NAND flash memory chip market [16]. This incident precisely explains as to why both practitioners and supply managers should not undermine the risk identification process from both firm- and network-level perspectives. Without a coordinated contingency policy and disruption recovery planning, supply chains cannot avoid negative consequences of events associated with supply, process, and demand risks [10,17].

Risk management has "evolved from passively reacting to vague general issues of disruptions towards more proactively managing SC risk from system perspectives" (Tang and Musa 2011, p. 30 [18]).

Thus, today's risk management approach must contain a competitive ex-ante mechanism in identifying vulnerable suppliers in anticipation of disruption. That is, the success of risk management depends on how well the supply network is equipped with a managerial decision-making approach in measuring and managing SC vulnerability [10]. For example, when SC is equipped with successful risk management strategies and vulnerability controls (i.e., limited resource, lead-time pressure), SC as a whole is able to cope with and quickly respond to disruption with a competitive level of SC capabilities [19–21]. To achieve SC resilience, SC disruption awareness alone is not enough and that it requires the firm's resource reconfiguration capabilities and a firm's risk management infrastructure to identify and monitor SC vulnerability [21].

Risk identification is the "first and the most important" stage of the risk management and it should be carried out for each the SC elements such as suppliers, manufacturers, warehouses, distribution channels [17]. Especially in the competing market, a direct competitor of a buying firm may force a supplier, that is vertically integrated by a direct competitor, to terminate the ongoing relationship with the buying firm to increase vulnerability [22]. In response to a recent political dispute or an economic trade war between Japan and Korea, South Korea chipmakers identified a risk in supply dependency of specific chemicals (photoresists, hydrogen fluoride, fluorinated polyimides) and recognized the value of collaborating with multiple suppliers rather than a single supplier [23]. The chipmakers have begun to diversify sourcing network in China and Taiwan as an effort to build a resilient supply network system rather than being reliant on Japanese suppliers. With recent trends of globalization, e-trade, advanced technology, and emerging production techniques supply networks are becoming more fragile and vulnerable to risks [17]. Thus, the risk identification process has gained academic attention in the form of strategic supplier management approaches: Bayesian network to identify a supplier with a higher likelihood of separation from a disaster zone [24], multiple sourcing strategy which initially identifies the level of supplier dependency proposes an optimal sourcing diversification [25,26], and optimal order quantity allocation which identifies the level of required emergency inventory using mixed integer programming [27].

Despite the on-going scholarly efforts in designing and planning a resilient supply network that can withstand disruptions, the following questions are still needed to be answered in this field.

First, the dynamic capability management approach lacks the inclusion of network structural relationship perspective and practical design and planning of resilient supply chains. To date, various operations and supply chain management (OSCM) scholars have identified the key characteristics and drivers of SC resilience from a qualitative perspective. The characteristics of interconnected suppliers in a focal firm's supply chain network can directly and indirectly influence the network vulnerability [10]. Hosseini et al. [28] identified agility, visibility, flexibility, collaboration, and information sharing as the key drivers that contribute to building SC resilience taxonomy from the quantitative perspective. Ali et al. [3] identified situation awareness, robustness, knowledge management, security, visibility, flexibility, redundancy, collaboration, agility, contingency planning, market position, and social capital as core elements to SC resilience mapping framework based on literature review of 103 articles. Similarly, Shin and Park [4] proposed a digraph that illustrates the interrelationship of 24 SC resilience capabilities based on literature-based interpretive structural modeling. While abovementioned studies propose conceptual clarity in SC resilience definition, essential elements, and managerial practices but are limited in guiding practitioners to strategic decision with respect to supplier management in a complex network context. Moreover, given the broad scope and extensive coverage of these SC capabilities, practitioners are in need of refined lists that are more relevant to their specific SC design and management decisions.

Second, existing multicriteria decision making (MCDM) studies in risk management focus on providing optimal supplier selection or resource allocation issues rather than assisting practitioners understand the state of the art in identifying vulnerable suppliers in a complex supplier network. Whilst there is an ongoing research in establishing comprehensive yet exhaustive criteria list from economic, environmental, and social perspectives [29–32], only few studies mention and incorporate the nature of supply network design and its characteristics. Despite the gained attention of network or geographical complexity of modern supply chain design, there exists a limited guideline for the incorporation of network criteria such as geographical location or structural design [6,33,34]. Aligned with Hosseini et al.'s [28] recent acknowledgement that there lacks an investigation of MCDM methods in the context of SC resilience, this study illustrates a useful tool for evaluating SC vulnerability and means to achieve resilient performance simultaneously.

This study aims to contribute to the risk management field by (i) identifying main SC attributes that a supply manager should account for prior to designing and planning a resilient supply network, and (ii) proposing a MCDM approach to delineate vulnerable supplier and propose prioritization approach to supply network management. To this end, a bicriterion network resilience (BNR) model is developed, based on a ranking approach that considers superiority and inferiority intensities of supplier based on both SC capabilities in a centralized network structure. The investigated network structure depicts a real-world case of three tiers of 17 suppliers and distributors of an Air Conditioning and Energy product that are found in a global market.

The remainder of this paper is organized as follows: Section 2 presents this study's literature background. This study develops our bicriterion resilience model in Section 3, and Section 4 proposes the prioritization approach and its application. Section 5 discusses the results of the case evaluation of global manufacturing company. Finally, Section 5 concludes our findings and addresses theoretical and practical implications, as well as its limitations and opportunities for future research.

2. Literature Review

2.1. Supply Chain Network Resilience

A 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 [35]. Due to the nature of the network settings, interconnected firms can expect to receive benefits such as innovation [1,36], and face risks such as increased vulnerability [10,37]. Specifically, Erol et al. [38] state that although an extended enterprise structure may benefit from potential business opportunities through the increased level of connectivity, it may also suffer from being exposed to new threats.

As part of the effort to deal with the variety and level of uncertainties, many studies have investigated and developed the necessary capabilities that supply networks must acquire to remain resilient. The investigations of resilience enablers have widened globally such as external, internal, and flexibility capabilities in food and beverage, retail, and general manufacturing in France [39], technological capabilities of electronics manufacturing in India [40], preparedness, alertness, agility of 20 different industries in the United States [41], and robust, agile, lean, flexibility of European premium drink producer [42].

In addition to the technology driven firm level capabilities, the effectiveness of collaboration gained attention as well. For example, SC disruption orientation [21], institutional pressure [43], collaboration, culture, information sharing [44], and collaborative communication, mutually created knowledge, joint relationship efforts [45] have been proven to be an interdependent factor in achieving overall network resilience. Consequently, Eltantawy [11] concluded the importance of cultural competence, operational competence, and situation awareness in the process of aiding the buyer's firm to adapt to a turbulent environment.

From a network structural perspective, prior research focuses on the characteristics of disruption and their effects depending on the type of network typologies. Ellis et al. [46] empirically verified how the probability of disruption and the magnitude of its impact encouraged buyers to seek alternative suppliers. Based on a transaction cost economy and resource dependence theory, they identified the characteristics of the supply market and the products that increase the likelihood and effects of disruptions. Nair and Vidal [47] simulated how network characteristics (average path length, clustering coefficient, size of the largest connected component, and maximum distance between the nodes) affected the robustness of supply networks (measured by insignificant differences in the mean of the performance measure). Kim et al. [6] compared four fundamental supply network structures to analyze the importance of node and arc disruptions for network-level disruption. They proposed that, assuming every firm (node) and its connection (link) had an equal probability of failure, network resilience was determined by the degree distribution. Hearnshaw and Wilson [35] argued that an efficient SC followed 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, the structural design of a network and its properties can shed light on the resilience management of a complex network from both theoretical and managerial perspectives.

Despite the consensus on the importance of a network perspective, studies on SC sustainability and resilience have been limited to analysis at the firm level. Most lacked practical suggestions for considering integrative capability and network measures. Moreover, while recent studies highlight theoretical and empirical findings with regard to SC capabilities and resilience, the implications for managerial application remain unclear.

2.2. SC Network Resilience and SC Capabilities

SC network resilience can be represented with two characteristics that are often shaped by the interconnected suppliers' capabilities: SC network complexity (i.e., number of suppliers and their distances within a supply chain) and node criticality (the degree of dependence by other suppliers) collectively affect supply network rerouting and communication times in a disruption [48]. These characteristics and their degrees of complexity and criticality are significantly shaped by four SC capabilities: flexibility, agility, efficiency, and alertness.

Flexibility is defined as the ease of altering the number and range of possible alternatives (i.e., number of possible alternatives and the degree of differences between alternatives) in the SC to cope with a variety of market changes and events while delivering acceptable performance [20]. Specifically, Purvis et al. [42] defined flexibility as the SC's ability to modify or adapt without trade-offs such as increased costs and lead times. Similarly, flexibility has been often described as the number of stable states a supply could readily take in response to a number of changes that might arise [20,45,49]. From another perspective, how a supplier manages disruption and responds to uncertain demands are core capabilities of flexibility [50]. From the buyer's perspective, Hohenstein et al. [44] emphasized the pertinence of obtaining flexibility through backup suppliers, production systems and distribution channels [19,51,52]. Lastly, Pereira et al. [53] distinguished four main properties of SC flexibility: sourcing flexibility, product flexibility, process flexibility, and transportation flexibility [8,54–57].

Increasing network complexity not only enhances vulnerability, but also reduces SC agility [37]. Agility is defined as the ability to respond to changes in a timely way by adapting SC processes [41]. Several studies have interlinked agility and flexibility. For example, Blackhurst et al. [58] defined agility as a higher-level SC capability (compared with flexibility) consisting of visibility (i.e., communication and information sharing), velocity (i.e., acceleration and responsiveness), and redesign (i.e., supply chain redesign) elements. Purvis et al. (2016) described agility as a function of flexibility and noted 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" [59]. However, previous articles stated that while an agile supply chain had to be flexible, a flexible supply chain did not necessarily guarantee agility [44,60]. Thus, flexibility and agility must be treated as two distinct capabilities. Specifically, several scholars have considered response speed as inherent to SC agility [61]. Li et al. [62] contended that agile firms had to be able to respond to actual events or disruptions in a timely manner, and Christopher and Holweg [63] stated that SC agility was a critical capability for the global sourcing process. As an example of agility practice, agile firms must carry safety stocks to buffer against uncertain events to reduce the probabilities of stock outs and lost sales [44].

Efficiency refers to lean suppliers containing little or no excess inventory which then enable utilization of extra capacity in the post-disruptive phase [42]. Efficiency is often viewed alongside robustness, as robustness requires redundancy. However, during the response and recovery phases of disruptions, efficiency plays a key role in minimizing the overall financial loss and complementing other SC capabilities that contribute to resilience. The balanced level of inventories with efficiency has been identified in several studies of SC capabilities. For example, balancing redundant resources with the level of efficiency is referred to as a prerequisite of resilience [45]. Moreover, flexibility attributes have needed to be efficient to ensure an effective response to disruptions [19]. Lastly, SC velocity is built based on the efficiency of the SC's response and recovery [20,64].

With the increasing size of supply networks, greater attention has been given to undermining alertness and awareness practices. Despite the current communication information systems and routines of network members, having a means of alerting each other or a monitoring process as part of awareness practice is sometimes considered to be of 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 [11,41,65]. Both the buyer and supplier firms should be aware of various levels of risks, such as risks related to assets, processes, organizations and the environment [66] and should collaboratively work to improve knowledge transfer among SC partners [67]. Awareness enhances preparation for emergencies, which consequently improves the supplier's resilience capabilities [68].

2.3. SC Network Resilience Management and Supplier Management Prioritization Approach

One of the remaining critical issues faced by the OSCM managers is in effectively operationalizing and incorporating interconnected firm's capability and network structural attributes in the supplier management process [69]. To address this multidimensional nature of supply network evaluation process, analytical tool that can effectively integrate both internal and environmental measures into the decision process can prove useful from the supply network risk management perspective. Mainly, there are two major evaluation models for SC network resilience management, such as dynamic capability improvement model and network optimization model.

The dynamic capability improvement model often focuses on identifying and acknowledging prominent influential factors to improve overall firm capabilities and performance. Such models require an effortful task for interpretation, thus, systematic analyses are often adopted to alleviate vagueness in its findings. Rajesh [40] developed total interpretive structural modeling to identify and categorize major technological capabilities of firms that influence the overall supply chain resilience capabilities. They identified SC design modification and planning capabilities as the prominent relations among various factors based on a case evaluation of electronics manufacturing industry in India. Brusset and Teller [39] examined a conceptual model between SC capabilities and resilience, contingent on the perception of supplier risk. Grounded in the resource-based view of firms, their research highlighted the importance of the perception of supplier in decision-making with respect to integration and deployment of capabilities for SC resilience.

The network optimization model relies on the assumption that the interdependence structure significantly drives and moderates the overall network performance. Recent research streams follow that the supply chain exhibits the properties of a complex adaptive system (nonlinearity, adaptation, self-organization, emergence) [70], and that such system now should be thoroughly investigated based on a set of interdependent firms and their interactions. Hsu and Wen [71] adopted grey theory and multiobjective programming to improve overall airline flexibility considering passenger's service level, operating cost, airline route length, concentration of traffic flow. Hosseini and Barker [24] adopted a Bayesian network to model the causal relationship of primary (cost, quality, lead time), green (CO_2emission, environmental practice) and resilience attributes of each connected firm in supplier evaluation context. Their application aided in quantifying the appropriateness of suppliers based on such criteria, empowering the ability select suppliers based on the expert evidence. Capaldo and

Giannoccaro [72] operationalized the NK fitness landscape model to quantitatively demonstrate the effectiveness of degree of interdependence and interdependence patterns on the relationship between trust level and SC performance.

However, in the context of resilience management, the optimal status of attributes such as resilience and network values are ambiguous and difficult to specify; thus, both positive and negative measures of the quantified relationship should be considered. Abovementioned approaches lack the integrative perspective of network structural relationship and network design. Consequently, practitioners can benefit from a revised approach that delineates vulnerable suppliers and provides a guideline to supply network management for a sustainable performance.

From this aspect, the proposed approach in this study provides a value adding alternatives to a specific network management problem: (i) it can deal with both ordinal and cardinal attributes in decision making. In SC resilience, practitioners may prefer diverse evaluation mechanisms, based on which they can indicate their varying preferences for the firms of interest [73]; (ii) there is virtually no limitation on the number of attributes that can be considered in the decision-making process; (iii) the concepts of concordance and discordance approach (also known as superiority–inferiority ranking) deem appropriate to SC resilience because the interrelationships between firms (or suppliers) are often subject to positive (concordant) and negative (discordant) business relations; (iv) other comparative prioritization approaches are generally based on the distance to an optimal status, which only considers the positive situation for all attributes.

3. The Proposed Framework

In this section, the bicriterion network resilience (BNR) model is proposed to compute and visualize the resilience and network relations between firms. An ordering approach, concordance and discordance, is then applied to determine firms' priorities for enhancing the overall supply network resilience. The ultimate goal of network representation is to help practitioners maintain a prescribed balance among firms. In doing so, a confidence level on supplier network resilience performance can be justified. Each step of the network resilience priority assessment is detailed as in the following.

Step 1. Identifying potential suppliers for the network under investigation

As the first step of the proposed framework, a supply network manager or a committee consisting more than one manager must identify involved or key suppliers for the orders and products under investigation. Then N is treated as a a finite set of supply network connected firms (nodes).

Step 2. Identifying appropriate resilience and network criteria for supplier evaluation

Appropriate evaluation criteria must be determined prior to supply network evaluation. Aligned with Gören's [74] suggestion, primary criteria are developed based on literature review which is then validated by the company's expert for a final criterion. As a comprehensive list of resilience capabilities, various capabilities have been identified: collaboration, agility, alertness, information sharing, risk control, trust [75]; collaboration, flexibility, agility, visibility, velocity, redundancy, robustness, rapidity, responsiveness [48], situation awareness, robustness, knowledge management, security, visibility, flexibility, redundancy, collaboration, agility, contingency planning, market position, social capital [3]; flexibility, redundancy, agility, collaboration, information sharing, visibility [44]; flexibility, velocity, visibility [45]. On the contrary, only limited network attributes have been operationalized as network criteria for supplier.

Then we let C represent a finite set of criteria of a firm's value with given ordinal measurement scales and k be an criteria weight vector such that $k(c) > 0$ for all $c \in C$. For each supply network connected firm, n, evaluate c criteria based on the resilience and network attributes (μ, γ) and the corresponding weights $k(c)$.

Step 3. Determining the values of the criteria using linguistic and network assessment

For the evaluation of capability criteria, this study adopts a probabilistic approach which can effectively utilize empirical data. Based on the empirical data, a normal probability distribution is formed for each criterion, and thus, the probability that node n_i is true can be expressed as firm i resilience attribute μ with a value of φ. As the node's resilience capability is measured using the SC capabilities, the individual firm's resilience likelihood can be estimated.

$$\begin{aligned} P(n_i) &= survival\ likelihood\ of\ node\ n_i\ in\ case\ of\ a\ disruption \\ &= Pr(\mu_{ir} \le \varphi_{ir})\ \forall i \end{aligned} \quad (1)$$

The evaluation of network criteria is determined based on various quantitative measurements of network attributes include the average degree, network diameter, network centralization, network heterogeneity, degree exponent, and assortativity [76].

Step 4. Establish the concordance and discordance set of each firm

The concordant–discordant distance was originally developed to assign Superiority–Inferiority 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 [77].

First, the levels of superiority ($S_c(i)$, S-count) and inferiority ($I_c(i)$, I-count) of each firm over other firms for each attribute c are calculated. S-count is simply the number of firms to which firm n is superior, 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.

$$S_c(i) = \{i \succ_c b\}\ where\ i, b\ \in N \quad (2)$$

$$I_c(i) = \{b \succ_c i\}\ where\ i, b\ \in N \quad (3)$$

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

Step 5. Establish the importance weights for the concordance and discordance of each firm

Then the corresponding importance weights (π^+, π^-) based on the concordance and discordance sets ($C^+\ C^-$) are calculated as defined in the previous step. For node n, the total relevant concordance and discordance weights are calculated based on the following equation:

$$\pi^+(i) = \sum_{c\ \in\ C^+(i)} \pi_c \quad (4)$$

$$\pi^-(i) = \sum_{c\ \in\ C^-(i)} \pi_c \quad (5)$$

$$\pi_c = \frac{k(c)}{\max k(c)} \quad (6)$$

Step 6. Establish the final weighted concordance and discordance level of each firm

With S-count, I-count, π^+, and π^- defined, the final weighted level of concordance and discordance (χ^+, χ^-) of each firm are calculated as follows:

$$\chi^+(i) = \sum_{c\ \in\ C^+(i)} (S_c(i) - I_c(i))\ \pi_c \quad (7)$$

$$\chi^-(i) = \sum_{c\ \in\ C^-(i)} (I_c(i) - S_c(i))\ \pi_c \quad (8)$$

Step 7. Finalize the weighted concordance–discordance matrix

Form a matrix based on π^+, π^-, χ^+, and χ^- to evaluate the agreement (conflict) status between positive and negative perspectives.

Step 8. 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. Case Study

4.1. Problem Definition

The real-world case employed in this study was solicited from the air conditioning division of a global manufacturing firm based in Korea. Globally renowned for the high quality of its air conditioners, washing machines, refrigerators, smart TVs, and mobile phones, this firm has extensive global production and sales activities, with global sales worth USD 57.7 billion in 2017. Further, this firm is highly connected to a complex global supplier network, and consequently operates and assigns designated supply network strategy teams to each division for risk and sustainability management. Based on interviews with general managers from the supply management and procurement divisions of home appliance department, a final network of a representative product that consists of 19 suppliers and their network structures were identified (Figure 1). To gain a better understanding regarding the conceptual design of supplier network from a practitioner′s perspective, this study initially adopted prior theoretical knowledge on supply network design and requested practitioners' comments based on their experiences. Interview topics included a general question around what is the most common supplier network structure that is observed among business divisions that make transactions on both global and local level. Once the dominant suppliers and its interrelationships are identified regarding its degree of connectivity, then the practitioners were requested to evaluate the level of transaction value and the size of each firm.

The suppliers of the focal firm are mainly composed of manufacturers (MFG) and assembly factories which have their own network of suppliers. Manufacturers are represented by the main parts they are responsible for: component parts (Part), motor system (motor), product frame (frame), jet engine (jet), integrated circuit chip (IC chip), pipe components (pipe), and main final product (main). The characteristics of a network structure includes a mixture of centralized and potential block-diagonal relationships. Suppliers are divided into three tiers. The first tier consists of the firm's own local and global assembly and production sites. Notably, suppliers 8 and 15 are significantly larger than the others as they primarily serve as main 'hubs', acting as moderators in the network. Suppliers 9–11 and 12–14 are located near each other, displaying potential business or social relationships.

4.2. Evaluating and Ranking of Suppliers

This section describes the step-by-step priority assessment explained in Section 3. Hereafter, firm is referred as a node to actively depict the network system perspective. The proposed bicriterion network resilience model aims to develop a systematic and visual assessment of a supply network system based on dual objectives of maximizing firm's resilience performance and minimizing firm's exposure to structural design driven vulnerability. Researchers state that a supplier relationship can no longer be viewed as a chain-like linear relationship, but as a complex network of relationships. Consistent with this view, this study is based on a network model, but it differs in terms of defining and integrating the resilience value (based on SC capabilities) and the network value (attributes of network structures). In this section, the adopted resilience attributes are explained and then the types of network attributes considered for this study are elaborated. Then, we provide a step-by-step order of prioritization with a case example based on the concordance–discordance approach introduced by Rebai et al. [78]. Finally, a decision support system is provided as a means to distinguish the firms that require immediate attention from a risk assessment perspective.

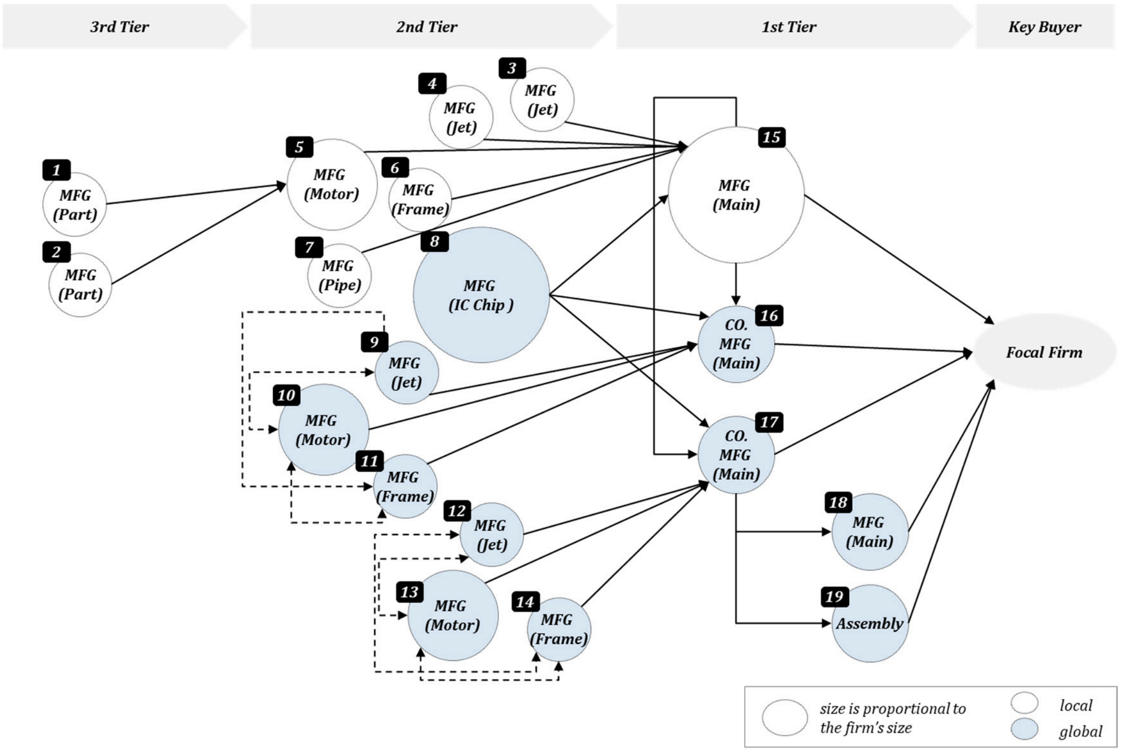

Figure 1. Network structure of the evaluated case.

A fundamental issue with the BNR model is that the two criteria (resilience and network values) have completely different and often conflicting aspects because the resilience value is based on the subjective judgment of resilience, while the network value is based on the quantitative interpretation of network positional relationships. Our aim is to propose a network resilience model that can achieve two goals: (i) understand the suppliers' current level of resilience and (ii) prioritize the suppliers (nodes) to maintain a balanced level of network resilience.

4.2.1. Criteria Used

Resilience Capability Criteria: Operational capabilities of the suppliers that affect the interconnected firms' resilience performance ($resilience\ value = f(\mu_r)$).

In previous literature, the measurement of SC resilience has been operationalized using two approaches: (1) subjective measures of SC capabilities that enable resilience performance [19,21], and (2) objective measures of capacities such as absorptive, adaptive, and restorative capacities, which are summed to provide an overall measure of the resilience performance [79,80]. However, Hosseini et al. [81] emphasized that the performance measurement model and its accuracy were insignificant unless supplemented with an applicable planning policy. Hence, this study focuses on adopting and operationalizing subjective resilience attributes to stay within the study's scope of developing a resilience-based management policy.

- Flexibility [C1, $f(\mu_{i1})$]: Flexibility is the degree of easiness in managing alternatives under environmental and operational uncertainties [45,61] (i.e., how easily can SCs change its volume and process?)
- Agility [C2, $f(\mu_{i2})$]: Ability is the timeliness in managing alternatives and system reconfiguration to sudden changes in supply and demand [41,82] (i.e., how fast can SCs respond and adapt?)

- Efficiency [C3, $f(\mu_{i3})$]: Efficiency is the level of resources utilized for the derived operational results [83] (i.e., how easily can SCs control resources while managing lean management practices?)
- Alertness [C4, $f(\mu_{i4})$]: Alertness the degree of readiness in dealing with environmental and operational risks and emergencies [84] (i.e., how fast can SCs detect disruptive events?)

To determine a single supplier i's overall resilience value, the resilience value of a node i, μ_i, is measured by the weighted sum of the resilience capabilities of supplier i, where k_{ir} represents the weight of capability criteria r. The degree of each resilience capability r for firm i is determined by the linguistic scale of firm's experts with the following scales: 0 = nonexistent, 1 = very low capability, 3 = low capability, 5 = average capability, 7 = high capability, 9 = very high capability, 10 = maximal capability.

$$\mu_i = \sum_{r=1} k_{ir}\mu_{ir} \ \forall i \tag{9}$$

Network Criteria: Network characteristics that enable effective sourcing and/or rerouting options in disruptive events ($network\ value = f(\gamma_t)$).

Among various network attributes, this study is mainly interested in the degree of centrality and betweenness centrality as proposed by Kim et al. [85] for the following reasons. First, most real-world network structures follow a scale-free model whose properties depend on the characteristics of the nodes [86]. Specifically, a scale-free model follows a power law distribution with a certain value of degree exponent that includes the growth rate of the node's degree with respect to the 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, other metrics are temporarily disregarded as their validity relies heavily on complete and accurate information on the network system.

The following measures of network characteristics (t) at the node level are adopted for the measurement model.

- Degree of centrality [C5, $f(\gamma_{i1})$]: The degree centrality of a node i, γ_{i1}, is measured by the number of direct links that are connected to node i. x_{ij} takes a binary value of 1 if there is a link between nodes i and j, and 0 otherwise.

$$\gamma_{i1} = \sum_{j=1} x_{ij} = \sum_{j=1} x_{ji} \ \forall i \tag{10}$$

- Betweenness centrality [C6, $f(\gamma_{i2})$]: The betweenness centrality of a node i, γ_{i2}, is measured by the total number of links that contain node i. g_{jk} is the total number of geodesics, shortest path length, between node j and k, while $g_{jk}(i)$ is the number of geodesics that contain node i. node i's betweenness is simply the probability that the node lies between other nodes.

$$\gamma_{i2} = \sum_{j<k} \frac{g_{jk}(i)}{g_{jk}} \ \forall i \tag{11}$$

For each firm, both degree of centrality and betweenness centrality are calculated using Equations (10) and (11) to quantitatively represent the network complexity that is provided by firm i. To determine a single firm i's overall network value, the network value of a node i, γ_i, is measured by a weighted sum of network criteria of firm i, where k_{it} represents the weight of network criteria t.

$$\gamma_i = \sum_{t=1} k_{it}\gamma_{it} \ \forall i \tag{12}$$

4.2.2. Ranking of Suppliers

Each node is evaluated based on four capabilities (μ_{i1}, μ_{i2}, μ_{i3}, μ_{i4}) and network attributes (γ_{i1}, γ_{i2}) on a scale ranging from 0 to 10. In this case, a prior information matrix is formed, as presented in

Table 1, with weights that can be obtained by a group of experts' linguistic assessment illustrated in Section 4.2.1. For example, the average evaluation of flexibility capability (r = 1) for firm 1 is 9 representing a very high degree of firm's ability to change its volume and process. While firm 15 has the lowest degree of centrality (k = 1) with value of 0, firms 1, 2, 3, 4, 6, and 7 have highest degree of centrality with value of 8.89. High degree of centrality and betweenness centrality reflect the significant network value in creating a complexity within the SC network. As a base case scenario, equal weights are computed, and the average weighted performances of the attributes are also listed in the table.

Table 1. Prior rating information matrix of L Electronics' connected nodes.

Supplier (i)	C1 (μ_{i1})	C2 (μ_{i2})	C3 (μ_{i3})	C4 (μ_{i4})	C5 (γ_{i1})	C6 (γ_{i2})	Weighted Average
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

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

Table 2. Count matrix of $S_c(a)$ and $I_c(a)$ with results in the R-columns.

	Resilience Values												Network Values					
	C1 (μ_{i1})			C2 (μ_{i2})			C3 (μ_{i3})			C4 (μ_{i4})			C5 (γ_{i1})			C6 (γ_{i2})		
Supplier (i)	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

Based on the nodes' rating information, the importance weights (π^+, π^-) and preferences (χ^+,χ^-) are presented in Table 3.

Table 3. Final concordant and discordant pair matrix and prioritization order.

Supplier	$\pi^+(i)$	$\pi^-(i)$	$\chi^+(i)$	$\chi^-(i)$	Gap	Observation
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
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	7.17	6.17	308.17	228.17	80.00	Concordant
10	6.17	7.33	228.17	322.67	−94.50	Discordant
11	6.83	7.00	280.17	294.00	−13.83	Discordant
12	4.00	9.33	96.00	522.67	−426.67	Discordant
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
16	4.17	12.67	104.17	962.67	−858.50	Discordant
17	4.33	12.83	112.67	988.17	−875.50	Discordant
18	4.00	10.83	96.00	704.17	−608.17	Discordant
19	7.00	8.00	294.00	384.00	−90.00	Discordant

The results show that 10 nodes display extreme discordance levels with respect to concordance levels:

$$S17 > S16 > S18 > S15 > S12 > S3 > S10 > S19 > S8 > S11.$$

Suppliers with high discordance and low concordance levels have significantly negative resilience and network values, thus requiring an improvement in the overall value of the supply network model.

The second set of suppliers that need attention are those with similar levels of concordance and discordance.

$$S5 > S9 > S2 > S13 > S14 > S7 > S1 > S6 > S4.$$

Although these firms perform better than others on some attributes, they perform worse than others on other attributes. This type of conflicting output creates uncertainty about the level of performance when disruption occurs. Thus, these firms should be carefully monitored and accurately measured in terms of their resilience capabilities and network values. Suppliers with higher concordance values than 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 are likely to reduce their exposure to risks and mitigate their vulnerabilities.

5. Conclusions and Limitations

The main purpose of this study was to provide an alternative in delineating vulnerable supplier and proposing prioritization approach to supply network management. Aligned with the dual objectives of resilience approaches against disruptions [87], this study proposes an integrative perspective to achieve a desirable level of SC capabilities in adopting and recovering post-disruption, and to mitigate the uncertainty level of risk through the network structural relationships. The proposed approach is similar to the node-place model in transportation studies, in which the model utilizes each station's node value (the train station's capacity) and place value (surrounding environmental attributes) to identify and provide a means of improving the stations with a balanced level of node and place values [88,89].

Resultantly, an integrative model that encompasses both the operational and environmental attributes of supply networks was proposed. Each firm carries a certain potential for performance based on its 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 was introduced to encourage a comprehensive assessment to inform supply network management. Second, the concordance–discordance approach was incorporated to identify firms that are uniquely conflicted (high discordance) in terms of performance levels with respect to other connected firms. This approach is useful when delineating firms that may impose an unexpected level of disruption for given levels of capabilities.

This study contributes to theory as well as practice by increasing the understanding of how to integrate resilience capabilities and network values to determine the supply network resilience level in preparation for disruptions. Moreover, for practical application, this study proposed a network resilience model along with a concordance and discordance approach that can be used to prioritize firms to create a balanced and resilient network system. While numerous traditional studies on SCs have attempted to identify the key SC capabilities that enable resilience and the implications of the structural relationships in a network, an integrative outlook can 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 help to identify firms with balanced capabilities and a feasible amount of exposure to vulnerability, or firms with unbalanced capabilities and high exposure to vulnerability.

Future studies are encouraged to investigate the following research questions with regard to the validity and generalizability of the model. (i) How accurately can the BNR model predict actual practitioners' qualitative perspective? Does the priority assessment of the network model change according to the industry type? It is important to adjust the model to minimize the gap between the theory-based suggestions and the real-world perspective. (ii) How do the values of networks and resilience change as network structures change? The design of network structures varies depending on the industry or firm's strategy. Thus, the validity of the model can be tested in varying network settings. (iii) How would the resilience model change with respect to different cultures or exchange relationships? Future studies are recommended to include cultural or exchange relationships in the resilient management model. Hohenstein et al. [44] noted that culture-specific studies on global SCs could improve SC resilience strategies in different national cultural contexts. Although modern SCs call for complex global relationships, or exchange relationships, whether they are based on cultural or regional differences should be evaluated further.

Author Contributions: All authors conceived, developed, analyzed the research model; contributed to the discussion and design of the framework; and wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors thank the Institute of Management Research at Seoul National University for supporting this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bellamy, M.A.; Ghosh, S.; Hora, M. The influence of supply network structure on firm innovation. *J. Oper. Manag.* **2014**, *32*, 357–373. [CrossRef]
2. Yoon, J.; Yildiz, H.; Talluri, S.S. Risk Management Strategies in Transportation Capacity Decisions: An Analytical Approach. *J. Bus. Logist.* **2016**, *37*, 364–381. [CrossRef]
3. Ali, A.; Mahfouz, A.; Arisha, A. Analysing supply chain resilience: Integrating the constructs in a concept mapping framework via a systematic literature review. *Supply Chain Manag. Int. J.* **2017**, *22*, 16–39. [CrossRef]
4. Shin, N.; Park, S. Evidence-Based Resilience Management for Supply Chain Sustainability: An Interpretive Structural Modelling Approach. *Sustainability* **2019**, *11*, 484. [CrossRef]

5. Reyes Levalle, R.; Nof, S.Y. Resilience in supply networks: Definition, dimensions, and levels. *Annu. Rev. Control* **2017**, *43*, 224–236. [CrossRef]
6. Kim, Y.; Chen, Y.S.; Linderman, K. Supply network disruption and resilience: A network structural perspective. *J. Oper. Manag.* **2015**, *33–34*, 43–59. [CrossRef]
7. Greening, P.; Rutherford, C. Disruptions and supply networks: A multi-level, multi-theoretical relational perspective. *Int. J. Logist. Manag.* **2011**, *22*, 104–126. [CrossRef]
8. Pettit, T.J.; Fiksel, J.; Croxton, K.L. Ensuring supply chain resilience: Development of a conceptual framework. *J. Bus. Logist.* **2010**, *31*, 1–21. [CrossRef]
9. Pettit, T.J.; Croxton, K.L.; Fiksel, J. The Evolution of Resilience in Supply Chain Management: A Retrospective on Ensuring Supply Chain Resilience. *J. Bus. Logist.* **2019**, *40*, 56–65. [CrossRef]
10. Wagner, S.M.; Neshat, N. Assessing the vulnerability of supply chains using graph theory. *Int. J. Prod. Econ.* **2010**, *126*, 121–129. [CrossRef]
11. Eltantawy, R.A. The role of supply management resilience in attaining ambidexterity: A dynamic capabilities approach. *J. Bus. Ind. Mark.* **2016**, *31*, 123–134. [CrossRef]
12. Amindoust, A. A resilient-sustainable based supplier selection model using a hybrid intelligent method. *Comput. Ind. Eng.* **2018**, *126*, 122–135. [CrossRef]
13. Dolgui, A.; Ivanov, D.; Sokolov, B. Ripple effect in the supply chain: An analysis and recent literature. *Int. J. Prod. Res.* **2018**, *56*, 414–430. [CrossRef]
14. Hou, Y.; Wang, X.; Wu, Y.J.; He, P. How does the trust affect the topology of supply chain network and its resilience? An agent-based approach. *Transp. Res. Part E Logist. Transp. Rev.* **2018**, *116*, 229–241. [CrossRef]
15. Baek, B. Samsung, SK hynix rush to find new suppliers. *The Korea Times*, July 2019.
16. Kim, H. Stock Woes Deepen in South Korea as a New Trade War Roils Market. *Bloomberg*, July 2019.
17. Kırılmaz, O.; Erol, S. A proactive approach to supply chain risk management: Shifting orders among suppliers to mitigate the supply side risks. *J. Purch. Supply Manag.* **2017**, *23*, 54–65. [CrossRef]
18. Tang, O.; Musa, S.N. Identifying risk issues and research advancements in supply chain risk management. *Int. J. Prod. Econ.* **2011**, *133*, 25–34. [CrossRef]
19. Pettit, T.J.; Croxton, K.L.; Fiksel, J. Ensuring supply chain resilience: Development and implementation of an assessment tool. *J. Bus. Logist.* **2013**, *34*, 46–76. [CrossRef]
20. Jüttner, U.; Maklan, S. Supply chain resilience in the global financial crisis: An empirical study. *Supply Chain Manag. Int. J.* **2011**, *16*, 246–259. [CrossRef]
21. Ambulkar, S.; Blackhurst, J.; Grawe, S. Firm's resilience to supply chain disruptions: Scale development and empirical examination. *J. Oper. Manag.* **2015**, *33–34*, 111–122. [CrossRef]
22. Chopra, S.; Sodhi, M.S. Managing risk to avoid supply-chain breakdown. *MIT Sloan Management Review*, 15 October 2004.
23. Park, J.; Yamazaki, M. Supply-chain pain: South Korea chipmakers and their suppliers seek to bypass Tokyo curbs. *Reuters*, 8 July 2019.
24. Hosseini, S.; Barker, K. A Bayesian network model for resilience-based supplier selection. *Int. J. Prod. Econ.* **2016**, *180*, 68–87. [CrossRef]
25. Ivanov, D.; Sokolov, B. Control and system-theoretic identification of the supply chain dynamics domain for planning, analysis and adaptation of performance under uncertainty. *Eur. J. Oper. Res.* **2013**, *224*, 313–323. [CrossRef]
26. Ivanov, D.; Sokolov, B.; Dolgui, A. The ripple effect in supply chains: Trade-off 'efficiency-flexibility-resilience' in disruption management. *Int. J. Prod. Res.* **2014**, *52*, 2154–2172. [CrossRef]
27. Sawik, T. Selection of resilient supply portfolio under disruption risks. *Omega* **2013**, *41*, 259–269. [CrossRef]
28. Hosseini, S.; Ivanov, D.; Dolgui, A. Review of quantitative methods for supply chain resilience analysis. *Transp. Res. Part E Logist. Transp. Rev.* **2019**, *125*, 285–307. [CrossRef]
29. Zimmer, K.; Fröhling, M.; Schultmann, F. Sustainable supplier management—A review of models supporting sustainable supplier selection, monitoring and development. *Int. J. Prod. Res.* **2016**, *54*, 1412–1442. [CrossRef]
30. Fallahpour, A.; Udoncy Olugu, E.; Nurmaya Musa, S.; Yew Wong, K.; Noori, S. A decision support model for sustainable supplier selection in sustainable supply chain management. *Comput. Ind. Eng.* **2017**, *105*, 391–410. [CrossRef]
31. Luthra, S.; Govindan, K.; Kannan, D.; Mangla, S.K.; Garg, C.P. An integrated framework for sustainable supplier selection and evaluation in supply chains. *J. Clean. Prod.* **2017**, *140*, 1686–1698. [CrossRef]

32. Sopadang, A.; Wichaisri, S.; Banomyong, R. Sustainable supply chain performance measurement a case study of the sugar industry. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Rabat, Morocco, 11–13 April 2017; pp. 1079–1080.
33. Nielsen, I.E.; Banaeian, N.; Golińska, P.; Mobli, H.; Omid, M. Green Supplier Selection Criteria: From a Literature Review to a Flexible Framework for Determination of Suitable Criteria. In *Logistics Operations, Supply Chain Management and Sustainability*; Golinska, P., Ed.; EcoProduction; Springer International Publishing: Cham, Switzerland, 2014; pp. 79–99. ISBN 978-3-319-07286-9.
34. Cardoso, S.R.; Paula Barbosa-Póvoa, A.; Relvas, S.; Novais, A.Q. Resilience metrics in the assessment of complex supply-chains performance operating under demand uncertainty. *Omega* **2015**, *56*, 53–73. [CrossRef]
35. Hearnshaw, E.J.S.; Wilson, M.M.J. A complex network approach to supply chain network theory. *Int. J. Oper. Prod. Manag.* **2013**, *33*, 442–469. [CrossRef]
36. Gao, G.Y.; Xie, E.; Zhou, K.Z. How does technological diversity in supplier network drive buyer innovation? Relational process and contingencies. *J. Oper. Manag.* **2015**, *36*, 165–177. [CrossRef]
37. Yang, B.; Yang, Y. Postponement in supply chain risk management: A complexity perspective. *Int. J. Prod. Res.* **2010**, *48*, 1901–1912. [CrossRef]
38. Erol, O.; Sauser, B.J.; Mansouri, M. A framework for investigation into extended enterprise resilience. *Enterp. Inf. Syst.* **2010**, *4*, 111–136. [CrossRef]
39. Brusset, X.; Teller, C. Supply chain capabilities, risks, and resilience. *Int. J. Prod. Econ.* **2017**, *184*, 59–68. [CrossRef]
40. Rajesh, R. Technological capabilities and supply chain resilience of firms: A relational analysis using Total Interpretive Structural Modeling (TISM). *Technol. Forecast. Soc. Change* **2017**, *118*, 161–169. [CrossRef]
41. Li, X.; Wu, Q.; Holsapple, C.W.; Goldsby, T. An empirical examination of firm financial performance along dimensions of supply chain resilience. *Manag. Res. Rev.* **2017**, *40*, 254–269. [CrossRef]
42. Purvis, L.; Spall, S.; Naim, M.; Spiegler, V. Developing a resilient supply chain strategy during 'boom' and 'bust'. *Prod. Plan. Control* **2016**, *27*, 579–590. [CrossRef]
43. Jazairy, A.; von Haartman, R. Analysing the institutional pressures on shippers and logistics service providers to implement green supply chain management practices. *Int. J. Logist. Res. Appl.* **2019**, 1–41. [CrossRef]
44. Hohenstein, N.-O.; Feisel, E.; Hartmann, E.; Giunipero, L. Research on the phenomenon of supply chain resilience. *Int. J. Phys. Distrib. Logist. Manag.* **2015**, *45*, 90–117. [CrossRef]
45. Scholten, K.; Schilder, S. The role of collaboration in supply chain resilience. *Supply Chain Manag. Int. J.* **2015**, *20*, 471–484. [CrossRef]
46. Ellis, S.C.; Henry, R.M.; Shockley, J. Buyer perceptions of supply disruption risk: A behavioral view and empirical assessment. *J. Oper. Manag.* **2010**, *28*, 34–46. [CrossRef]
47. Nair, A.; Vidal, J.M. Supply network topology and robustness against disruptions—An investigation using multi-agent model. *Int. J. Prod. Res.* **2011**, *49*, 1391–1404. [CrossRef]
48. Stone, J.; Rahimifard, S. Resilience in agri-food supply chains: A critical analysis of the literature and synthesis of a novel framework. *Supply Chain Manag. Int. J.* **2018**, SCM-06-2017-0201. [CrossRef]
49. Carvalho, H.; Azevedo, S.G.; Cruz-Machado, V. Agile and resilient approaches to supply chain management: Influence on performance and competitiveness. *Logist. Res.* **2012**, *4*, 49–62. [CrossRef]
50. Rajesh, R.; Ravi, V.; Venkata Rao, R. Selection of risk mitigation strategy in electronic supply chains using grey theory and digraph-matrix approaches. *Int. J. Prod. Res.* **2015**, *53*, 238–257. [CrossRef]
51. Sheffi, Y.; Rice, J.B., Jr. A supply chain view of the resilient enterprise. *MIT Sloan Manag. Rev.* **2005**, *47*, 41–48.
52. Tang, C.; Tomlin, B. The power of flexibility for mitigating supply chain risks. *Int. J. Prod. Econ.* **2008**, *116*, 12–27. [CrossRef]
53. Roberta Pereira, C.; Christopher, M.; Lago Da Silva, A. Achieving supply chain resilience: The role of procurement. *Supply Chain Manag. Int. J.* **2014**, *19*, 626–642. [CrossRef]
54. Chiang, C.; Kocabasoglu-Hillmer, C.; Suresh, N. An empirical investigation of the impact of strategic sourcing and flexibility on firm's supply chain agility. *Int. J. Oper. Prod. Manag.* **2012**, *32*, 49–78. [CrossRef]
55. Simangunsong, E.; Hendry, L.C.; Stevenson, M. Supply-chain uncertainty: A review and theoretical foundation for future research. *Int. J. Prod. Res.* **2012**, *50*, 4493–4523. [CrossRef]
56. Spiegler, V.L.M.; Naim, M.M.; Wikner, J. A control engineering approach to the assessment of supply chain resilience. *Int. J. Prod. Res.* **2012**, *50*, 6162–6187. [CrossRef]

57. Rice, J.B., Jr.; Caniato, F. Building a secure and resilient supply network. *Supply Chain Manag. Int. J.* **2003**, *7*, 22–30. [CrossRef]
58. Blackhurst, J.; Dunn, K.S.; Craighead, C.W. An empirically derived framework of global supply resiliency. *J. Bus. Logist.* **2011**, *32*, 374–391. [CrossRef]
59. Baker, P. Designing distribution centres for agile supply chains. *Intenational J. Logist.* **2006**, *9*, 207–221. [CrossRef]
60. Swafford, P.M.; Ghosh, S.; Murthy, N. The antecedents of supply chain agility of a firm: Scale development and model testing. *J. Oper. Manag.* **2006**, *24*, 170–188. [CrossRef]
61. Manuj, I.; Mentzer, J.T. Global supply chain risk management strategies. *Int. J. Phys. Distrib. Logist. Manag.* **2008**, *38*, 192–223. [CrossRef]
62. Li, G.; Lin, Y.; Wang, S.; Yan, H. Enhancing agility by timely sharing of supply information. *Supply Chain Manag. Int. J.* **2006**, *11*, 425–435. [CrossRef]
63. Christopher, M.; Holweg, M. "Supply Chain 2.0": Managing supply chains in the era of turbulence. *Int. J. Phys. Distrib. Logist. Manag.* **2011**, *41*, 63–82. [CrossRef]
64. Stevenson, M.; Spring, M. Flexibility from a Supply Chain Perspective: Definition and Review. *Int. J. Oper. Prod. Manag.* **2007**, *27*, 685–713. [CrossRef]
65. Li, X.; Goldsby, T.J.; Holsapple, C.W. Supply chain agility: Scale development. *Int. J. Logist. Manag.* **2009**, *20*, 408–424. [CrossRef]
66. Rajesh, R.; Ravi, V. Modeling enablers of supply chain risk mitigation in electronic supply chains: A Grey-DEMATEL approach. *Comput. Ind. Eng.* **2015**, *87*, 126–139. [CrossRef]
67. Duryan, M.; Smyth, H. Cultivating sustainable communities of practice within hierarchical bureaucracies: The crucial role of an executive sponsorship. *Int. J. Manag. Proj. Bus.* **2018**, *12*, 400–422. [CrossRef]
68. Rajesh, R.; Ravi, V. Supplier selection in resilient supply chains: A grey relational analysis approach. *J. Clean. Prod.* **2015**, *86*, 343–359. [CrossRef]
69. Onstein, A.T.C.; Ektesaby, M.; Rezaei, J.; Tavasszy, L.A.; van Damme, D.A. Importance of factors driving firms' decisions on spatial distribution structures. *Int. J. Logist. Res. Appl.* **2020**, *23*, 24–43. [CrossRef]
70. Choi, T.Y.; Dooley, K.J.; Rungtusanatham, M. Supply networks and complex adaptive systems: Control versus emergence. *J. Oper. Manag.* **2001**, *19*, 351–366. [CrossRef]
71. Hsu, C.I.; Wen, Y.H. Application of Grey theory and multiobjective programming towards airline network design. *Eur. J. Oper. Res.* **2000**, *127*, 44–68. [CrossRef]
72. Capaldo, A.; Giannoccaro, I. How does trust affect performance in the supply chain? the moderating role of interdependence. *Int. J. Prod. Econ.* **2015**, *166*, 36–49. [CrossRef]
73. Erker, S.; Stangl, R.; Stoeglehner, G. Resilience in the light of energy crises—Part II: Application of the regional energy resilience assessment. *J. Clean. Prod.* **2017**, *164*, 495–507. [CrossRef]
74. Gören, H.G. A decision framework for sustainable supplier selection and order allocation with lost sales. *J. Clean. Prod.* **2018**, *183*, 1156–1169. [CrossRef]
75. Machado, S.M.; Paiva, E.L.; da Silva, E.M. Counterfeiting: Addressing mitigation and resilience in supply chains. *Int. J. Phys. Distrib. Logist. Manag.* **2018**, *48*, 139–163. [CrossRef]
76. Perera, S.; Perera, H.N.; Kasthurirathna, D. Structural characteristics of complex supply chain networks. In Proceedings of the 2017 Moratuwa Engineering Research Conference (MERCon), Moratuwa, Sri Lanka, 29–31 May 2017; pp. 135–140. [CrossRef]
77. Tsoukiàs, A.; Perny, P.; Vincke, P. From Concordance/Discordance to the Modelling of Positive and Negative Reasons in Decision Aiding. In *Annals of Mathematics and Artificial Intelligence*; Springer: Boston, MA, USA, 2002; Volume 77, pp. 147–174.
78. Rebai, A.; Aouni, B.; Martel, J.-M. A multi-attribute method for choosing among potential alternatives with ordinal evaluation. *Eur. J. Oper. Res.* **2006**, *174*, 360–373. [CrossRef]
79. Spiegler, V.L.M.; Potter, A.T.; Naim, M.M.; Towill, D.R. The value of nonlinear control theory in investigating the underlying dynamics and resilience of a grocery supply chain. *Int. J. Prod. Res.* **2016**, *54*, 265–286. [CrossRef]
80. Cimellaro, G.P.; Asce, A.M.; Renschler, C.; Reinhorn, A.M.; Asce, F.; Arendt, L. PEOPLES: A Framework for Evaluating Resilience Introduction and Definition of Resilience. *J. Struct. Eng.* **2016**, *142*, 04016063. [CrossRef]

81. Hosseini, S.; Barker, K.; Ramirez-Marquez, J.E. A review of definitions and measures of system resilience. *Reliab. Eng. Syst. Saf.* **2016**, *145*, 47–61. [CrossRef]
82. Melnyk, S.A.; Davis, E.W.; Spekman, R.E.; Sandor, J. Outcome-Driven Supply Chains. *MIT Sloan Management Review*, 1 January 2010.
83. Gligor, D.M.; Esmark, C.L.; Holcomb, M.C. Performance outcomes of supply chain agility: When should you be agile? *J. Oper. Manag.* **2015**, *33–34*, 71–82. [CrossRef]
84. Matook, S.; Lasch, R.; Tamaschke, R. Supplier development with benchmarking as part of a comprehensive supplier risk management framework. *Int. J. Oper. Prod. Manag.* **2009**, *29*, 241–267. [CrossRef]
85. Kim, Y.; Choi, T.Y.; Yan, T.; Dooley, K. Structural investigation of supply networks: A social network analysis approach. *J. Oper. Manag.* **2011**, *29*, 194–211. [CrossRef]
86. Perera, S.; Bell, M.G.H.; Bliemer, M.C.J. Network science approach to modelling the topology and robustness of supply chain networks: A review and perspective. *Appl. Netw. Sci.* **2017**, *2*, 33. [CrossRef]
87. Haimes, Y.Y. On the definition of vulnerabilities in measuring risks to infrastructures. *Risk Anal.* **2006**, *26*, 293–296. [CrossRef]
88. Bertolini, L. Spatial Development Patterns and Public Transport: The Application of an Analytical Model in the Netherlands. *Plan. Pract. Res.* **1999**, *14*, 199–210. [CrossRef]
89. Papa, E.; Bertolini, L. Accessibility and Transit-Oriented Development in European metropolitan areas. *J. Transp. Geogr.* **2015**, *47*, 70–83. [CrossRef]