Resilience and cleaner production in industry 4.0: Role of supply chain mapping and visibility

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Abstract

Industry 4.0 makes the business processes more autonomous, automated, and intelligent. Supply chain mapping can be a steppingstone to adopt the developments of Industry 4.0. Despite its profound significance in Industry 4.0 driven supply chain management, it has been hardly discussed in the research literature. Against this backdrop, the objective of this study is to test the impact of supply chain mapping on a firm's supply chain visibility and resilience. Data were collected from 154 Electrical & Electronics sector Malaysian firms through a close-ended questionnaire. The study employed structural equation modeling to analyze the hypothesized relationships. A significant momentous effect of supply chain mapping was found on the supply chain visibility and supply chain resilience. Further, the study also found a significant mediating role of supply chain visibility in the association between SC mapping and supply chain resilience. The findings of the study strongly suggest firms adopt a supply chain mapping strategy to improve supply chain visibility and supply chain resilience. Findings also suggest maintaining closer ties with key suppliers in order to increase SC visibility.

Keywords: Industry 4.0; Cleaner Production; Supply Chain mapping; Resilience

Introduction

Majority of the business leaders seem sustainability as the lynchpin corporate strategy to embrace the developments of the fourth industrial revolution (Industry 4.0); however, a thin majority of the businesses have adopted it (Kiron et al., 2017; Fatorachian and Kazemi 2018; Luthra et al.,2019; Luthra et al., 2020). Transforming the business on the lines of sustainability is a challenging task; however, the adoption of cleaner production (CP) strategies can play an instrumental role in this regard. The cleaner production entails efficient business processes, better process visualization and monitoring, and better employees' health and safety (Fragapane et al., 2020; Luthra and Mangla, 2018; Klemeš et al., 2012; Oliveira et al., 2016; Jin et al., 2017; Fatorachian and Kazemi, 2018; Ivanov, and Dolgui, 2020).

Researchers (e.g., Mubarik and Zuraida 2019; Manavalan, & Jayakrishna 2019; Ivanov, and Dolgui, 2020) argue that a firm should transform its supply chain on the lines of cleaner production, in order to be sustainable in the fourth industrial era, which further requires strategically mapped (supply chain mapping) and resilient supply chain.

Owing to the nature and scope of the supply chain mapping, it is considered as an agent of cleaner production. According to the definitions of UNEP *"Cleaner Production can be applied to the processes used in any industry, to products themselves and to various services provided in society."* Supply chain mapping (SCMap) is one of the cleaner production strategies that is applied at business processes and helps in conserving raw materials, and energy; identifying and eliminating toxic and dangerous raw materials; and reducing the quantity and toxicity of all emissions and wastes at source across the supply chain (Mubarik 2020; Bappy et al., 2019). Likewise, supply chain mapping identifies the environmental concerns and helps to integrate into the designing and delivery of the products from factor to the customer.

Further both SC mapping and visibility are considered essential components of a socially sustainable supply chain, which has the overarching aim of promoting cleaner and sustainable production (Bian et al., 2020; Chalmard and 2019). This study discusses the juxtaposition of supply chain mapping with supply chain visibility and resilience. The building blocks of both SC mapping and visibility are industry 4.0 technologies. SC mapping provides the venue for the application of Industry 4.0 technologies to attain cleaner production (Hahn 2020).

Studies (e.g., Sanderson 2020; Mubarik 2020; Fabbe-Costes and Spring 2020) denote that supply chain mapping can yield the twofold advantages. First, it profoundly improves the visualization and monitoring of the processes across the value chain, which is the essence of cleaner production. Secondly, it improves the resilience of a supply chain, which is essential for the adoption of the fourth industrial revolution. Supply chain mapping not only plays a breakthrough role in improving a firm's supply chain visibility and sustainability but also uplifts its supply chain resilience. Despite the critical role of SC mapping both in building supply chain resilience and improving the sustainability of a supply chain, studies did not focus on this aspect until recently (Khan et al.,2020). The increasing environmental concerns and disruptions caused by COVID19 are pushing both practitioners and researchers to study the role of supply chain mapping in the context of supply chain resilience, sustainability and cleaner production (Khan et al.,2020; Choi et al. 2020). Supply chain mapping provides an in-depth picture of SC to understand the areas of cost savings. Likewise, it also offers companies much flexibility by monitoring threats and avoiding or minimizing the effects of possible disruption (Fragapane et al., 2020). According to Choi et al. (2020), *"[companies] have better visibility into the structure of their supply chains. Instead of scrambling at the last minute, they have a lot of information at their fingertips within minutes of potential disruption. They know exactly which suppliers, sites, parts, and products are at risk, which allows them to put themselves first in line to secure constrained inventory and capacity at alternate sites."*

Nevertheless, looking into the complexities of a supply chain (SC), supply chain mapping appears to be a cumbersome and challenging task (Manavalan, & Jayakrishna 2019; Ivanov, and Dolgui, 2020). As a matter of fact, for producing one reasonably complex product, tens of thousands of parts are required. The majority of the components are sourced from the geographically spread an extensive network of suppliers. These suppliers themselves further outsource their material to second-tier suppliers. It results in an increasingly complex, geographically spread, and multi-tiered supply network (Christopher and Lee 2004; Mubarik and Naghavi 2019; Ivanov, and Dolgui, 2020). Due to the length and breadth of this network, companies started losing visibility over the topology of their supply network. This invisibility of supply networks severely hampers an organization's capacity to respond to any supply chain disruption and to ensure the sustainability of the processes. This is the reason that firms' supply chain departments are struggling hard to cope with COVID19 effects and putting their best to secure the supplies of components and raw materials to keep their supply chains afloat. However, the unavailability or inaccessibility to the key information is creating a big hurdle to respond to the disruption caused by COVID19. It is leading to a reactive, unorganized, and subtle response to the unprecedented disruptions, thus compromising the supply chain resilience to a greater extent.

Further, despite various supply chain disruptions caused by natural disasters, political crisis or epidemic diseases, the majority of the firms are yet appeared to be underprepared in terms of supply chain mapping and visibility to cope up with covid19. The study of Choi et al. (2020) highlights the graveness of the situation. According to this study, 70 percent of their respondents were yet in the phase of information collection to analyze their supplier's position, whether they were in the locked-down regions of China or not. There can be numerous reasons for this problem; however, the major problem can be a lack of supply chain mapping.

Interestingly, it is hard to find any research study explicitly discussing the supply chain mapping and its impacts upon the supply chain visibility and resilience. The present study undertakes these tasks and by taking the Electrical and Electronics sector of Malaysia as a case. According to the Malaysian Investment Development Authority [MIDA] (2020), the electrical and electronics industry of Malaysia is among the leading contributor to the country's GDP, export, and employment. The sector also contributes substantially to the global exports of the electrical and electronics industry.

The study contributes to the literature on cleaner production in industry 4.0, supply chain mapping, and supply chain visibility in many ways. First, despite the context limited to the processed food industry of Malaysia, this is among the pioneering studies investigating the role of SC Mapping in improving SCV and SCRes. The findings of the study show that firms with higher SCMap experience significant improvements in SCV as compare to firms with lower SCMap. Secondly, this study provides empirical evidence on the association between SCV and SCRes. Over the horizon of our study, firms with higher SCV was found to be more resilient as compared to the firms with lower SCV. Third, the study analyzes the mediating role of SCV in the association between Supply chain mapping and supply chain resilience. Fourth, this study offers evidence on the benefits of supply chain mapping and visibility that was absent from literature until now. Our results have implications for SC managers as they demonstrate that the adoption of SC Mapping not only improves SC resilience of a firm but also leverages the firm's overall performance.

2. Literature Review

Industry 4.0 refers to the decentralization of business processes brought about by technological advances. It is characterized by technological innovations such as Machine to Machine communications, Internet of Things, Cyber-Physical Systems, artificial intelligence and Big Data Analytics (BDA) (Brettel et al. .2014). Industry 4.0 represents a business environment where employees, machinery, devices, and enterprise systems are connected through CPSs and the Internet (Oberg and Graham2016). It is enabling smart process management and has provided new paradigms for industrial management (Moeuf et al. .2017). Industry 4.0 driven-technologies, through integrating information and communication technologies within organizations, have enabled autonomous and dynamic manufacturing (Fatorachian and Kazemi 2018), and through transforming control systems in business operations have significantly improved the nature of products and services provided by organizations (Porter and Heppelmann 2014).

In the context of cleaner production, firms face critical impediments while shifting toward it. According to Bag and Pretorious (2020, p.2), "The main challenges are high initial setup costs; supply chain complexity; business-to-business non-cooperation; inadequate information for the design of products and manufacturing process; skill gaps; quality concessions; long lead times for disassembly; and high costs involved in such processes". These impediments can be subdued by adopting the industry 4.0 technologies especially I4.0-enabled supply chain mapping (Stock and Seliger, 2016; Nascimento et al., 2019; Jaeger and Upadhyay, 2020). For example, the use of the cyber-physical system in smart manufacturing can help in proper scheduling and execution of jobs resulting in resources and cost savings (Kusiak, 2018; Yao et al., 2019) leading to more adaptability of the natural resources availability and environmental costs. Likewise, smaller batches can lead to a more accurate response to the demand curves and consequently lessen the waste for production (Carvalho et al., 2018). Further, for Bag and Pretorious (2020, p.2), "[industry 4.0] I4.0 principles include interoperability, decentralization, virtualization, real-time capabilities, modularity and service orientation. Interoperability can help in the longer machine life cycle, decrease in an industrial waste generation; likewise, decentralization can help in improved usage of local resources, better use of available assets; virtualization can reduce industrial waste, easier promotion of state-of-the-art environmental practices, increased recycling opportunities; real-time capabilities causes better adaptation to the demand curves, better use of resources, faster response to energy supply changes; modularity leads to better usage of industrial resources, longer machine life cycle; and service orientation can improve the usage of final products, increased recycling and reuse opportunities".

Industry 4.0 technologies also play an instrumental role in digitalizing the supply chain processes (upstream, downstream and midstream) and uplift SC resilience. Further, it significantly improves the supply chain visibility by seamlessly mapping and integrating the supply chain process (Xie et al.,2020). In the proceeding paragraphs, we discuss how supply chain mapping is interrelated to industry 4.0 and is an agent of cleaner production.

2.1 Supply Chain Mapping

The incorporation of sustainability into supply chain management is one of the most dynamic and ethical research agenda. The overarching focus of sustainability is cleaner production, which can be significantly attained with the adoption of supply chain mapping. The effective mapping of the supply chain enables a firm to visualize its suppliers and customer's business processes. This visualization not only improves the monitoring of the business processes but also enables the firm to evaluate the sustainability of the business processes (Manavalan, & Jayakrishna 2019). Supply chain mapping refers to *"the process of engaging across companies and suppliers to document the exact source of every material, every process and every shipment involved in bringing goods to market"* (Ivanov, and Dolgui, 2020). Supply chain mapping, according to Gardener and Cooper (2003), is *"a representation of the linkages and members of a supply chain along with some information about the overall nature of the entire map"*. It represents the supply network relationships, flows, and dynamics in a simplified yet realistic manner by capturing the essence of the environment in which the supply chain operates. Supply chain mapping assists an organization in visualizing the "*the network that connects the business to its suppliers and its downstream customers and allows the identification of problematic areas and support process decisions*." Likewise, according to Craighead et al. (2007), the supply chain mapping process demonstrates how the various organizations are linked by the material flow, the relationships, and their directions (uni or bidirectional) of the material flow. Hence, supply chain mapping focuses on how material, information and money flow in the upstream, midstream and downstream of supply chains (Craighead et al., 2007; Schroeder 2000).

The prime focus of a supply chain map is to cover all facets of a supply chain (SC) structure and demonstrates the firms, processes, facilities, and flows. Conventionally three aspects as SC maps should include in order to be a useful tool for executing supply chain strategy (Fine 1998; Soto-Viruet et al. 2013; Sampaio et al., 2016). First includes firms like the focal firm itself, its suppliers; second, technologies used in the supply chain processes and third capabilities, e.g., JIT deliveries, plant management etc. Such supply chain maps are very specific, detailed, and have narrowly defined information. (Lambert and Cooper 2000).

Nevertheless, the supply chain mapping can be done according to the purpose, scope, and level of details (Gardner and Cooper 2003). According to Sheffi(2005), "the prime purpose of supply chain map is generally strategic, and they range from a geographic vulnerability map to maps that show *'the flow of parts out of given regions, depicting who is involved and the plants in other parts of the world that are dependent on them*." It is important to note that supply chain mapping is significantly different from traditional mapping, also called the process mapping (Sheffi 2005; Farris II 2010).

Primarily, SCMap can be differentiated from process mapping (PM) on three critical aspects. First is orientation, defined as the prime *'focus'* of the mapping process. SCMap focuses on capturing the flow of information, material, and finances in both directions of the supply chain (upward and downward) and through the company. Whereas process mapping is a process flow chart focusing upon the single process within the firm. It does not focus on the entire chain and is not extended beyond the firm. Second, a differentiating aspect is the "extent of details" that a map represents. SCMap concentrates on the broader measures like lead time, volumes, cost etc., by taking a broader perspective of the supply chain processes and their interconnectedness. SSCMap primarily focuses on the critical entities, and non-essential entities are excluded in order to keep the mapping focused (Lambert, Cooper, and Pagh 1998; Barroso, Machado, and Machado, 2011). The third and last differentiating factor is the broader aim of mapping. PM is done conventionally for tactical and operational purposes, whereas the SC maps are built for a strategic purpose. Supply chain mapping is done in association with the supply chain strategy in order to ensure the alignment and execution of SC strategy. Supply chain mapping is aimed to permit a firm to view the end-to-end supply chain and helps the firm in understating the various entities involved in the supply chain (Lambert, 2008). A firm with strong supply chain mapping can have the capacity to visualize the flow of the product, information, and funds not only from the immediate suppliers but also from tier 2 and tier 3 suppliers. Supply chain mapping can also play an instrumental role in the process of strategic planning, and it can also be effective in executing supply chain strategies.

Taken together, *supply chain mapping can be defined as* the *overall process* of creating and maintaining a supply chain map which provides the complete visibility of the supply chain. Further supply chain mapping focuses on how material, information, and money flows in both upstream and downstream direction and within the organizations. The emphasis of SCMapping is high-level measures such as volume, cost, and lead time. Further, the prime purpose of a supply chain strategy and aimed to increase the supply chain visibility of a firm by representing the complete supply chain (Lambert, 2008). It is also used to execute the supply chain strategy effectively.

2.2 Supply Chain Resilience

SCRes shows the preparedness of an organization's supply chain to cope up with unexpected SC disruption. It also entails the ability of a firm to respond to the disruption and bounce back effectively. It is closely linked with the SC disturbance—"*a consequential situation that significantly threatens the normal course of operations of the affected supply chain entities"* (Zsidisin, 2000; Barroso et al., 2008). Researchers (e.g., Peck 2005; Mitroff & Alpasan 2003) define resilience as the capability of an organization to recuperate from supply chain disturbances or to adjust quickly according to the adversities or disturbances. Researchers like Fiksel (2006) explain SCRes as the ability of a firm to respond to the SC disruptions effectively and also to grow by effectively bouncing back. Conventionally, the supply risk management approach was used to counter the supply chain disruptions. However, such conventional risk management and assessment tools remained incapacitated to cater to unpredictable events (Pettit, 2008). Supply chain resilience filled this gap by taking the concept of supply chain risk management to a new level. In this context, Ponomarov and Holcomb (2009) offer a comprehensive definition of the supply chain by taking a multidisciplinary approach. They define SCRes as *"the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness* *and control over structure and function."* Ponomarov and Holcomb (2009, p.3). On the same lines, Fiksel et al. (2015) define supply chain resilience as *"the capacity for an enterprise or set of business entities to survive, adapt, and grow in the face of turbulent change"*.

Further, it is important to denote that supply chain resilience is not only the 'ability to recover,' but it also entails a firm's flexibility ability to adjust according to the new environment (Hamel & Valikangas, 2003; Stoltz, 2004; Gunasekaran et al.,2015). From the above discussion, we could retrieve the three important dimensions that can be retrieved—first, supply chains' preparedness—the readiness of a supply chain to face the disruptions. Second, agility—the speed to which a supply chain counters the disruptions. Third, recovery—the ability of a supply chain to recover from the disruptions in the minimum period. These three dimensions together can help a firm to better face and rebound to the supply chain disruptions. Further, a resilient supply chain rebound better and quicker from disruptions and hardships. In this study, we have taken supply chain resilience as a firm's preparedness, response, and recovery to the supply chain disruptions.

2.2 Supply Chain Mapping and Supply Chain Resilience

Researchers (e.g., Schoenherr, and Swink, 2015; Zhang et al., 2018) argue that supply chain mapping (SCMap) can uplift all three dimensions of SCRes, namely organizations preparedness, flexibility, and responsiveness. Before discussing the juxtaposition of supply chain mapping and supply chain resilience, it is essential to discuss the supply chain disruptions. It is a proven fact that SC disruptions can be highly unpredictable but also dire effects on the supply chain performance. For subduing the negative offshoots of these disruptions, uplifting the resilience of the supply chain is of utmost importance (Ponomarov and Holcomb, 2009). Most recently, Choi et al., (2020) claim that supply chain mapping is one of the significant sources of supply chain resilience. A firm with an end-to-end mapped supply chain not only has better capability to respond to the unpredictable events but also can recover quickly from such events. Accurately mapped supply chain helps the firm to visualize the firm's suppliers, their geographical origins, technologies, their contribution to the firm's supply base, the flows of various material, finance, and information (Soto-Viruet et al., 2013).

In short, SCMap provides the macro-graphic visualization of the current state of a supply chain. It can act as the simulator to analyze the potential strength of a supply chain by giving disruption shocks to the supply chain (Swift, Guide and Muthulingam 2019). A firm can evaluate its supply chain resilience, and if SC does not seem to be resilient in simulating shocks, the firm can devise the appropriate strategies to uplift the resilience of its supply chain. In the case of the supply chain spanned to the various countries, it may not be possible for the supply chain managers to have a complete visualization of information, material, and finances. Such a situation can create a great hindrance while responding to any unpredictable supply chain disruption, thus compromising supply chain resilience (SCRes) (Zhong et al., 2015). In such a case, a comprehensive supply chain mapping, showing an organizations' suppliers, and flows of material, processes, information, and finances can play an instrumental role in uplifting the resilience of its supply chain (William et al. 2013).

Several researchers (Choi et al., 2020; Zhong et al.,2015; William et al.,2013; Doorey 2011) have explicitly mentioned the role of supply chain mapping in improving the supply chain resilience of a firm. For example, Fine (1998) denoted the number of cases where supply chain mapping allowed companies to figure out the critical raw material or component suppliers that were in the shaky financial or legal position and were about to go out of business. Notably, according to Fine (1998), these identified suppliers were the sole supplier of that critical equipment or raw material. This allowed firms to source alternative suppliers quickly and also investigate the strength of not only tier-one but also tier two suppliers of critical equipment and material (Fine 1998; Fiksel et al., 2015). Although the literature on the SCMap is scant, all the available studies explicitly mention its profound role in improving the supply chain resilience of a firm (Gunasekaran et al., 2015; Choi et al.,2020). This discussion leads us to draw the following hypothesis.

Hypothesis 1: Supply chain mapping improves supply chain resilience of the firm

2.3 SC Mapping, and SC Visibility

Supply chain visibility is defined as the acquisition and evaluation of supply chain information that helps in controlling supply chain disruption risks and improves decision making (Tohamy 2003). It is also referred to as "*the ability to trace the points of origin of materials used in a product*" (Lee & Rammohan, 2017). SCV has emerged a vital supply chain capability that improves the effectiveness of a supply chain and reducing the effects of supply chain disruptions.

SCV helps the firm to trace the origin of the materials and components, which further improves the firm's understanding of the supply chain partners (Doorey, 2011). It can help firms to circumvent the issues and problems that can occur at the location of their suppliers. Supply chain mapping is thought to enable greater supply chain visibility. Supply chain mapping identifies the various organizations in the supply chain network and their linkages, which a firm must comprehend in order to attain the supply chain visibility (Barroso, Machado, and Machado, 2011; Wichman et al., 2020). When a firm accurately maps its supply chain, it can also acquire an in-depth understanding and knowledge of its procurement function. This knowledge, in turn, improves the supply chain visibility (SCV) of the firm.

Increasing outsourcing and internationalization of firm operations are making management and visualization of the supply chain increasingly complex (Wichmann et al., 2020). In such a case, a well-mapped supply chain not only helps visualize the supply chain but also can be a source to transfer the knowledge among organizations and managers as appropriate. Supply chain mapping is thought to be the pre-requisite for supply chain visibility (Childerhouse and Towill, 2006). It helps the firm to understand both the upstream and the downstream supply chains, provides a shared vision of the supply chain, improves communication across various stakeholders, and offers strong foundations for the supply chain analysis. In short supply chain map provides complete visibility of supply chain entities, their interrelationships, and flows in the supply chain (Achilles 2013). Further, an effectively mapped supply chain permits to recognize the key SC bottlenecks and constraints, relevant supply chain entities. It also enables a firm to identify the supply chain complexities and dynamics (Christopher and Peck 2004; Barrso et al., 2011). Thus, a supply chain mapping improves a firm's end-to-end supply chain visibility (SCV) by illustrating the key processes, flows, and entities.
We conjecture that supply chain mapping improves both upstream and downstream supply chain visibility of a firm. Hence, we hypothesize:

Hypothesis 2: Supply chain mapping improves supply chain visibility of a firm

2.4 SC Visibility and SC Resilience

Supply chain visibility plays an instrumental role in building the supply chain resilience of a firm. It improves supply chain resilience in three ways. First, higher supply chain visibility provides an in-depth understanding of the company's own and its supplier's sourcing processes. This understanding permits the firm to assess the procurement practices effectively and elevates both supply chain preparedness and supply chain response of the firm. Likewise, it also enables the firm to negotiate the procurement contracts better, synchronize the sourcing process to eliminate unnecessary delays and bottlenecks, and allows firms to work with suppliers to develop the contingency plans for unseen events.

Secondly, visibility of the upstream supply chain operations can assist a firm to significantly cope up with the supply chain disruption risks that may direly affect the firm's souring operations. Hence, a firm can significantly save the cost that could have incurred due to backorders, stock outs, and excessive inventory holding.

Third, it also makes it easy for the firm to adopt quality management approaches like Six Sigma, total quality management etc. Such initiative requires extensive documentation and visibility, which SCV can provide to the firm. (e.g., Corbett, Montes-Sancho, & Kirsch, 2005; Hendricks & Singhal, 2001; Swink & Jacobs, 2012). Several extant studies (e.g., Doorey, 2011; Hoyt et al., 2008; Walker & Merkley, 2017) explicitly recognize the importance of SCV in SCRes and demonstrate as to how the lack of SCV lead to the failure of supply chain resilience or overall supply chain. It implies that firms with higher SCV can have better control over supply chain processes, which can further bring the operational agility and responsiveness in the supply chain.

One interesting phenomenon is observable among the majority of the studies conducted on the precedence of SCV. These studies surmise the importance of SCV from its absence in the firms' strategies. According to Swift, Guide, and Muthulingam (2019, p.2), "*although this approach is suitable to illustrate the consequences of insufficient visibility, it does not provide a complete picture of potential benefits from supply chain visibility*." Researches exploring the impact of SCV on improving the supply chain resilience and performance are either scant or absent from the literature. It is worth mention that despite the recognition of SCV in the extant literature, lesser has been explored about the impact of SCV on SCREs. One of the significant reason for it is the lack of willingness of firms to share the information about their supply chains, specifically SCV and SCRes. We undertake this task and investigate the impact of SC visibility on the supply chain resilience of a firm. Specifically, we examine as to how supply chain visibility affects all three cords of SCRes I,e, preparedness, responsiveness, and agility. Against this backdrop, we hypothesize:

Hypothesis 3: Supply chain visibility improves supply chain resilience of a firm

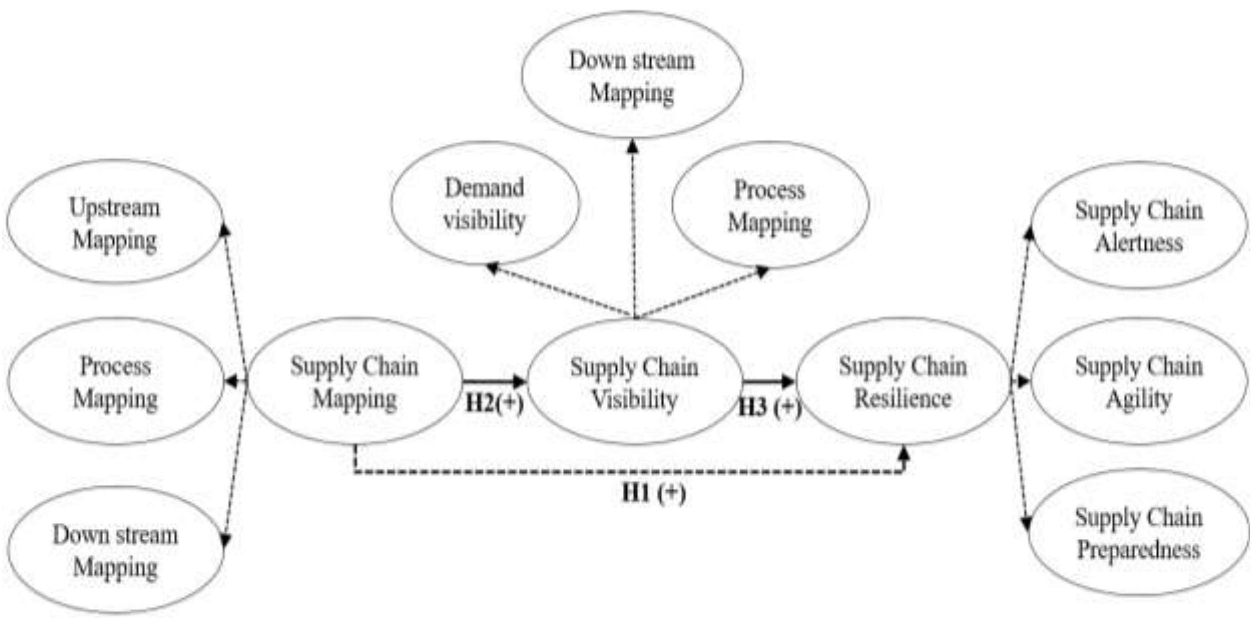

Figure 1: Conceptual Model

3. Methodology

3.1 Population and sampling

The study was conducted in the Electrical and Electronics sector of Malaysia. Malaysian E&E industry is one of the major contributors to the Malaysian manufacturing sector's GDP and export. According to the Malaysian Investment Development Authority [MITI] (2016), "*The E&E industry in Malaysia can be classified into four sub-sectors, namely, electronic components, consumer electronics, industrial electronics, and electrical products.*" The list of the registered companies was obtained from The Federation of Malaysian Manufacturers (FMM) and The Electrical and Electronics Association of Malaysia (TEEAM). We selected 70 firms from each sub-sector to collect the data; hence a total of 280 were approached for data collection from January 2020 to April 2020. Due to COVID19 outbreak, the data collection became highly challenging, especially collection through on-site visits. Therefore, the firms were approached electronically using various means. With persistent efforts, we could manage to collect data from 103 firms. Two questionnaires were excluded due to the high number of missing values. Table 1 shows the details of the respondent firms in terms of size, ownership, age, and sub-sector

Table 1: Sampling breakup (n=101)

Industry-wise breakup		
Consumer electronic	54	53%
Industrial electronic	47	47%
Size		
Medium*	33	33%
Large**	68	67%
Ownership		
Local (Malaysian owned)	41	41%
Joint venture (Local and foreign)	44	44%
Foreign Owned	16	16%
Firm Age(years)		
1 to 10	13	13%
11 to 19	57	56%
>20	31	31%
Department		
Supply Cain	39	38%
Planning	17	17%
Logistics	29	28%
Procurement	18	17%
Designation of respondents		
Deputy General Manager	8	8%
Senior Manager	21	20%
Manager	29	28%
Deputy Manager	34	33%
Assistant Manager	11	11%

,& show the employment size between 75 to 200 and >200 (Source: National SME Development Council (NSDC).*

3.2 Data Collection Instrument

Data were collected through the close-ended questionnaire. The constructs were adapted from the previous sources. Although the construct of supply chain mapping (SCMap) as it is not readily available, Farris (2010) has indicated that six major dimensions to be considered for effective supply chain mapping. These dimensions are, *"i) supply chain entities; ii) relational links between supply chain entities; iii) material flows; iv) information flows; v) management policies; and vi) lead times"* (Carvalho et al., 2012, p.359). In addition to that SCOR model (The Supply Chain Council 2006) also acts as a fundamental building block to measure supply chain mapping (Farris 2010; Wichmann et al., 2020). Keeping in view SCOR, supply chain mapping has been divided into three dimensions upstream mapping, downstream mapping, and midstream mapping. Upstream mapping measures focus on company mapping regarding its suppliers (tier 1) and suppliers' suppliers (tier 2). Likewise, downstream mapping measures the company's supply chain mapping with its customers and customers' customers. In this context, we adopted the construct of Mubarik (2020), which entails all of the above-discussed characteristics. The construct comprises of 25 items. The construct of supply chain visibility (SCV) was developed by William et al. (2013). It comprises three major dimensions, namely demand visibility, supply visibility, and market visibility, and 50 items.

Further, the construct of supply chain resilience (SCRes) was adopted from the studies of Wang et al.,(2010), Christopher and Peck, 2004, and Swafford et al. (2006), Gunasekaran et al. (2008), Gunasekaran et al. (2015), and Lee (2004) It consists of three major dimensions, namely supply chain preparedness, SC alertness, and SC agility, with a total of 15 items. All the items were measured on the Likert scale of 05, where 01 for strongly disagree to 05 for strongly agree. We included firms' size (SMEs and large) and age as the control variables.

In order to examine any non-response bias, we compared the characteristics of respondents (firm size, age, geographical dispersion, employees) with those of non-respondents. We could not find any statistically significant difference in the percentage of respondents and non-respondents across various categories. The results have been exhibited in the appendix C. One of the major reason for unbiased response rate was survey design, which helped the data collection team to follow-up the targeted respondents unequivocally.

3.3 Analytical Methods

We employed covariance-based structural equation modeling for analyzing the hypothesized relationships. The use of CB-SEM was preferred over other techniques due to its robustness. CB-SEM, in addition to other SEM approaches, also requires model fitness and univariate and group normality of the data for the analysis. It is also a preferable approach while testing the application of a newly developed model. CB-SEM is applied in two stages. At the first stage, reliability, validity, and fitness of the measurement models are ascertained. In the second stage, path analysis is conducted to test the developed hypotheses.

4. Findings

4.1 Measurement Model Analysis

In the first stage, we ascertained the measurement model's validity, reliability, and fitness. The reliability of the construct was examined by analyzing the values of CB alpha, CR, AVE, and factor loadings. The results in Table 2 show that all the constructs have the values of CB alpha, CR, and AVE higher than threshold values of 0.70, 0.70, and 0.50. Likewise, the factor loadings of all the retained items is higher than 0.66, which shows that all the items well load on their respective constructs. The validity of the measurement models has been ascertained through checking both convergent validity and discriminant validity. Convergent validity has been examined by evaluating the values of average variance extracted (AVE) The values of AVE higher than 0.50 show that all the measurement models have convergent validity (Table 2). Further, the discriminant validity we have employed the Fornell-Larcker criteria. Results in Table 3 show that the square root valued of AVE is higher than the inter-constructs correlations, thus ascertaining the discriminant validity. For the model fitness, four goodness of fit indices values, namely GFI, CFI, RMSEA, and χ/df ratio, have been evaluated. The values of GFI and CFI are greater than the recommended threshold values of 0.90. Likewise, the value of RMSEA should be less than 0.07, and χ/df ratio should be less than 5. The results in Table 2 show that all of the measurement models have the indices values within the band, thus confirming the measurement models' incremental, absolute, and parisomonial finesses.

Common method variance (CMV) occurs when responses systematically vary because of the use of a common scaling approach on measures derived from a single data source. In order to take care of CMV, we employed the Harman's one-factor test (Harman 1976). All items were loaded into one common factor. Highest total variance of any single factor was 19%, which rules out the possibility of CMV. Additionally, the values of VIF less than 3.3 also support the findings of Harman test (Podsakoff et al., 2012; Fuller et al., 2016).

Table 2: Reliability and Validity

Construct	Sub-construct	AVE	CR	CB Alpha	Fitness indices
Supply Chain Resilience	Supply chain alertness Supply chain agility Supply chain preparedness	0.57	0.93	0.83	*Chi-square/df=2.573* *RMEA=0.079* *CFI=0.88* *GFI=0.91*
Supply Chain Visibility	Demand Visibility Supply Visibility Market Visibility	0.55	0.92	0.81	*Chi-square/df=1.98* *RMEA=0.065* *CFI=0.91* *GFI=0.92*
Supply Chain Mapping	Process Mapping Upstream Mapping Downstream Mapping	0.58	0.89	0.79	*Chi-square/df=2.051* *RMEA=0.0581* *CFI=0.93* *GFI=0.952*

**Nine items from different constructs (SCA4, DV5,DV20,SV13,SV17,SV20,SCM4,SCM13,SCM22) were deleted due to low factor loading (FL<0.50). Loadings of the rest of the items were between 0.66 to 0.89.*

Table 3: Fornell-Larcker Criteria

	SCV	SCRes	SCMap
SCV	***0.755***		
SCRes	0.57	***0.742***	
SCMap	0.49	0.42	***0.762***

Note: Diagonal values are the square rooted values of AVE

4.2 Hypotheses Testing

The results of hypotheses testing are exhibited in Table 4. The results support the first hypothesis of the study, showing a significant direct impact of Supply chain mapping on supply chain resilience *(β=0.53, t-value=4.540).* Further results in Table 4 also show a significant positive impact of supply chain mapping on supply chain visibility *(β=0.67, t-value=3.960),* and supply chain visibility on supply chain resilience *(β=0.46, t-value=4.171).* To examine the impact of all independent variables collectively, the R-Square (effect size) is calculated. The values of R-Square are categorized as *0.35 strong effect size, 0.15 as moderate effect size, and 0.02 as the poor(low) effect* (Cohen, 1988). The values of R-square (0.62) given in Table 4 show a large effect of supply chain mapping and supply chain visibility on supply chain resilience.

Table 4: Hypotheses testing

	Hypotheses	Coefficient	t-value	Decision
Hypothesis 1	*Supply chain mapping improves supply chain resilience of firm*	0.53*	*4.540*	Supported
Hypothesis 2	*Supply chain mapping improves supply chain visibility of a firm*	0.67*	*3.960*	Supported
Hypothesis 3	*Supply chain visibility improves supply chain resilience of a firm*	0.46*	*5.171*	Supported
R-Square	0.62			
RMSEA	0.048			
CFI	0.941			
GFI	0.956			

*Note: * and ** show level of significance at 1% and 5% respectively*
^The threshold value for CFI, and GFI is 0.90.
^^For model fitness the value of RMSEA should be less than 0.08.

Table 5: Path Analysis

Path	β-value	p-value	Result
SC mapping→ SC Visibility→ SC Resilience	0.308***	0.000	Supported
Upstream mapping→ SC Visibility → SC Resilience	0.262***	0.000	Supported
Process mapping→ SC Visibility → SC Resilience	0.221***	0.000	Supported
Downstream mapping→ SC Visibility → SC Resilience	0.133	0.070	Not Supported
SC mapping→ SC Visibility	0.670***	0.000	Supported
Upstream mapping→ SC Visibility	0.570***	0.000	Supported
Process mapping→ SC Visibility	0.480***	0.000	Supported
Downstream mapping→ SC Visibility	0.124***	0.081	Supported
SC mapping→ SC Resilience	0.530***	0.000	Supported
Upstream mapping→ SC Resilience	0.440***	0.000	Supported
Process mapping→ SC Resilience	0.510***	0.000	Supported
Downstream mapping→ SC Resilience	0.128	0.081	Not Supported
SC Visibility → SC resilience	0.460***	0.000	Supported

**** show the level of significance at 1%*

In order to have an in-depth analysis of the triads of SC mapping, visibility and resilience, the results of Path analysis have been exhibited in Table 5. The results illustrate that only two dimensions significantly impact the SC visibility. Whereas the third dimensions i.e. downstream mapping, does not have any influence on the SC resilience both directly (β=0.133, p-value=0.07) and indirectly (β=0.128, p-value=0.08). These findings challenge the mainstream studies on the role of SC mapping in resilience. These studies (e.g. Choi et al., 2020) consider all three dimensions of SC mapping instrumental in developing the resilience of a supply chain.

5. Discussions

The findings of the study support our argument that supply chain mapping significantly contributes to the supply chain visibility and supply chain resilience. These results are not only in line with the conventional wisdom but also confirm the anecdotes of SCMap-SCRes relationship. Our findings echo the results of Choi et al. (2020), Farris II (2010) and Gardner and Cooper (2003) and show that SC Mapping can play an instrumental role in understanding both the upstream and the downstream supply chains. Further, it provides a shared vision of the supply chain and improves communication across various stakeholders. SC mapping significantly improves the supply chain visibility of a firm. Further, an effectively mapped supply chain allows a firm to identify the key supply chain bottlenecks and constraints, allowing the firm to visualize the supply chain complexities and dynamics (visibility).

The findings on the influence of supply chain visibility on supply chain resilience highlight the role of the former in improving the later. The supply chain visibility greatly assists a firm to significantly cope up with the supply chain disruption risks that may direly affect the firm's souring operations (William et al., 2013). Further, supply chain visibility, attained through effective supply chain mapping, permits a firm to look inward and outward simultaneously (Francis, 2008). It provides an in-depth understanding of the firm's and its supplier's sourcing processes. This understanding permits the firm to assess the procurement practices effectively and elevates both supply chain preparedness and supply chain response of the firm. Likewise, it also enables the firm to negotiate the procurement contracts better, synchronize the sourcing process to eliminate unnecessary delays and bottlenecks, and allows firms to work with suppliers to develop the contingency plans for unseen events (Gardner and Cooper 2003; Farris 2010).

Findings on the effect of supply chain mapping on resilience perfectly corroborate with the extant literature (e.g. Choi et al., 2020; Fiksel et al. 2015; Gardner and Cooper 2003; Farris 2010; Fine 1998) and reveal supply chain mapping as one of the significant sources of supply chain resilience. Some of the major contemporary studies, including Choi et al.,(2020) argue that a firm with end-to-end mapped supply chain not only has better capability to respond the unpredictable events but also can recover quickly from such events. Accurately mapped supply chain helps the firm to visualize the firm's suppliers, their geographical origins, technologies, and their contribution in the firm's supply base, the flows of various material, finance, and information (Gardner and Cooper 2003). In condensed form, SCMap provides a holistic visualization of the whole supply chain, which acts as the simulator to analyze the potential strength of a supply chain by giving disruption shocks to the supply chain (Swift, Guide and Muthulingam, 2019). This helps a firm to evaluate its supply chain resilience. In short, Supply chain mapping plays a key role in disseminating the essential information critical for survival in a turbulent and technologically dynamic environment (Ivanov 2020). An effective SC mapping can make the SC planner cautious about the potential constraints, bottlenecks, and hiccups in the supply chain. These capabilities of the supply chain simultaneously improve supply chain visibility and resilience (Choi et al.,2020). Further, SCMapping assists firms to identify the waste in upstream and downstream processes. It leads to re-engineering the business processes according to the needs of cleaner production, thus promoting the sustainable and ethical business agenda (Gardner and Cooper 2003; Cooper, Lambert, and Pagh 1997; Fine 1998; Choi et al.,2020; Ivanov 2020).

6. Implications

Our study has some profound implications for both managers and policymakers. Foremost is the adoption of supply chain mapping as an apex business strategy to adopt the trio of supply chain resilience, industry 4.0, and sustainability. Supply chain mapping offers strong foundations for supply chain analytics, which helps firms on two fronts. First, it assists firms in evaluating the resilience of their supply chain based on which they can evaluate the appropriate strategies for improving the resilience of a supply chain. Second, it allows firms to evaluate the sustainability of the firm and its suppliers' business processes, further allowing them to implement sustainable supply chain management practices (William et al., 2013; Christopher and Peck 2004). Third, supply chain mapping, together with digital technologies, big data, and business analytics, elevates a firm's readiness to adopt the industry 4.0.

In short, managers can improve the three fronts, namely supply chain resilience, sustainability, and industry 4.0, with the help of supply chain mapping. The biggest challenge in this regard could be the ability of a firm to obtain the real data spanning the supply chain. One of the solutions in this regard can be the use of macro-map, which according to Farris (2010) , can be instrumental in identifying *"the overall structure of the supply chain at the industry level to serve as a basis for exploring more detailed mapping of concentrated areas."* Presently, the majority of the corporate strategies are bent on adopting industry 4.0 developments and cleaner production simultaneously.

Likewise, the overwhelming objective of a supply chain strategy is to ensure the resilience of a supply chain. In this regard, based on the findings of our study, supply chain mapping can act as a bridge to connect the supply chain strategy with the corporate strategy. It leads us to recommend the manager for adopting the supply chain mapping as a cornerstone strategy for linking the corporate strategies and supply chain strategies. The studies of Ivanov, and Dolgui, 2020), Ivanov (2020), and Gardner and Cooper (2003) also echo the same fact mentioning. The denote, "*a well-constructed supply chain map with the right information, easily displayed and understood, should enhance the environmental scanning process of strategic planning"*.

Further supply chain mapping, together with the supply chain visibility, magnifies the inefficiencies in the micro part of the supply chain, allowing managers to adopt more robust, sustainable, and cleaner business processes. It is important to note that supply chain mapping cannot only be effective in adopting SC resilience, sustainability, and cleaner production but also play a very instrumental role in controlling the supply chain losses and chaos. The case of Tesco is a stunning example in this regard. In 2013, the company lost nearly 300 million Euro when, at some of its stores, horse meat was found in beef products. The complexity of its food supply chain, having various layers of suppliers, made it extremely challenging for the Tesco to identify and separate the origin of the horse meat. The inability to do so, lead the company to staggering financial and reputational losses to the firm (Fletcher, 2013). Putting together, we recommend firms adopt the supply chain mapping as a cornerstone strategy for improving supply chain resilience, overcoming supply chain losses, having sustainable and cleaner production, and adopting the industry 4.0 related developments. It is worth mentioning that the adoption of supply chain mapping requires some careful and prudent pace to avoid any significant setback. Specifically, firms should be cautious while sharing the data as there may be a chance of sharing competitive information with supply chain partners inadvertently.

7. Conclusion

Both practitioners and researchers envisage that Industry 4.0 can enable firms to attain efficiency gains and faster innovation. It is worth mentioning that this revolution is transmuting the global economic structure and is ineluctable for any organization. Since the concept of industry 4.0 and cleaner production are coming hand to hand, it is essential to adopt such supply chain management strategies, which are instrumental in *"adopting Industry 4.0 sustainably"*. Against this backdrop, the objective of the study was to analyze the influence of supply chain mapping in improving the supply chain resilience of a firm.

Further, the study also aimed to investigate the role of supply chain visibility in the association between supply chain mapping and supply chain resilience. We collected the data from 154 Malaysian Electronics and Electrical firms through a close-ended questionnaire and applied covariance-based structural equation modeling (CB-SEM) for analyzing the hypothesized relationships. Our results showed a profound influence of SCMapping on supply chain resilience. We also found a significant mediating role in the association between supply chain mapping and supply chain resilience. Knitting together, our findings reveal a significant role of SCMap in improving the supply chain resilience directly and indirectly. We also conclude an instrumental role in supply chain resilience in adopting the industry 4.0 developments. Our findings consider supply chain mapping a major pre-requisite for aligning a firm according to the need of industry 4.0 and also to adopt a cleaner production. Likewise, the accurately mapped supply chain can also be instrumental in adopting the concept of a circular economy. Visualizing the upstream and downstream supply chain can help significantly to adopt the circular economy. Finally, findings conclude that adoption of the Industry 4.0 approaches and concepts, firms make a form to be more resilient and sustainable and ethically responsible

8. Limitations and Future Research Directions

The study bears some limitations. The first limitation of the study is its predominant focus on the electronics and electrical sectors of Malaysia. Therefore, the results of the study may be generalized in other sectors cautiously. In this regard, we suggest that future researchers conduct two kinds of studies. First, to conduct a study focusing on all industries of manufacturing sector Malaysia. Such studies can analyze the results as overall and by industries. The findings of such studies can reveal the inter-industry difference in the results if any. Second, we suggest conducting cross country studies, focusing on one industry. Such studies can also be useful to highlight the instrumentality of supply chain mapping in attaining SC resilience, visibility, sustainability, and industry 4.0 globally. The second limitation of the study is the use of cross-sectional survey-based data for the analysis. We suggest future researchers use the time series data, from the selected firms, in order to analyze the behavior of a firm over time. The findings of such a study can be instrumental in checking the stability of the hypothesized relationships overtime.

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Appendix: Questionnaire

Supply Chain Visibility		1	2	3	4	5
Demand Visibility						
DV1	Our major customers share their point of sales/actual sales information with us.					
	The sales information we receive from our major customers is…					
DV2	...timely					
DV3	…accurate					
DV4	…complete (all the information we need)					
DV5	…in a useful format					
DV6	Our major customers share their demand forecasts with us					
	The forecast information we receive from our major customers is					
DV7	...timely					
DV8	…accurate					
DV9	…complete (all the information we need)					
DV10	…in a useful format					
DV11	Our major customers share their inventory level information with us					
	The customer inventory information is					
DV12	...timely					
DV13	…accurate					
DV14	…complete (all the information we need)					
DV15	…in a useful format					
DV16	Our major customers share information with us regarding their promotional plans					
	The promotional information we receive from major customers is					
DV17	...timely					
DV18	…accurate					
DV19	…complete (all the information we need)					
DV20	…in a useful format					
Supply Visibility						
SV1	Our major suppliers share inventory availability with us					
	The supplier inventory information is…					

SV2	...timely					
SV3	…accurate					
SV4	…complete (all the information we need)					
SV5	…in a useful format					
SV6	Our suppliers provide us with advance shipment notices					
	The advance shipment information we receive from suppliers is					
SV7	...timely					
SV8	…accurate					
SV9	…complete (all the information we need)					
SV10	…in a useful format					
SV11	Our major suppliers share information with us about order lead times/delivery dates					
	The order information we receive from major suppliers is					
SV12	...timely					
SV13	…accurate					
SV14	…complete (all the information we need)					
SV15	…in a useful format					
SV16	Our systems/partners provide us with finished goods locations status in the distribution network (e.g., distribution centers, transportation)					
	The information we have regarding finished goods locations status in the distribution network (e.g., distribution centers, transportation)					
SV17	...timely					
SV18	…accurate					
SV19	…complete (all the information we need)					
SV20	…in a useful format					
Market Visibility						
MV1	We get information from various sources to understand overall market level supply information					
	The overall market level supply information is					
MV2	...timely					
MV3	…accurate					
MV4	…complete (all the information we need)					
MV5	…in a useful format					
MV6	We gather information from various sources to understand overall market level demand information					
	The market level demand information we gather is					
MV7	...timely					
MV8	…accurate					
MV9	…complete (all the information we need)					
MV10	…in a useful format					
2. Supply Chain Mapping						

Upstream Supply Chain						
SCM1	We are able to visualize our upstream supply chain processes, and activities.					
SCM2	The mapping of our supply chain processes depicts geographical relationships with supplier, allowing spatial visualization.					
SCM3	Our firm is able to capture the real time information about the products and materials sourced, their quantities, and replenishment lead time.					
SCM4	SC mapping provides real time information sharing of suppliers					
SCM5	We are aware of the tier 2 suppliers of the critical components and raw material.					
SCM6	We have documented processes for dealing with suppliers.					
SCM7	We are able to visualize the real time flow of material from the suppliers.					
SCM8	We have a system for sharing real time information with suppliers.					
SCM9	Our SC mapping provides us a simplified representation of our upstream supply chain by capturing the essence of the environment in which the supply chain operates					
SCM10	We have mapped the flow of products, and information in the upstream supply chain.					
Midstream mapping						
SCM11	We have mapped processes showing the flow of material within the company.					
SCM12	We can real time track the flow of goods within our company from one department to other.					
SCM13	We have system of sharing real time information within the company, across several departments.					
SCM14	We can identify the supply chain processes inefficiencies in real time					
SCM15	Due to the mapping of mid-stream processes, we can monitor the effectiveness of our supply chain strategy					
SCM16	The mapping of our supply chain helps to catalog and distribute key information for survival in a dynamic environment.					
SCM17	Our SC mapping alerts our concerned managers to possible constraints in the system.					
SCM18	We have mapped the flow of products, and information in the mid-stream supply chain.					
Downstream-mapping						
SCM19	We have mapped the geographical dispersion of our customers.					
SCM20	We have mapped the geographical dispersion of our tier 2 customers.					
SCM21	We have system of sharing real time information with customers.					
SCM22	We can visualize the flow of goods from our company to customers' customers					
SCM23	The mapping of our downstream processes plays an essential role in providing guidance in the quantum changes in the downstream supply chain.					

SCM24	We have mapped the flow of products, and information, in the downstream supply chain.					
SCM25	The mapping of our downstream supply chain processes permits our company to identify areas for further analysis.					
C. Supply Chain Resilience						
1. Supply Chain Preparedness						
SCP1	Our company selects the firms that are easy to work with (i.e. willingness to accommodate the focal firm's business objectives) as supply chain partners.					
SCP2	Our company chooses reliable firms to establish a supply chain partnership.					
SCP3	Our company provides equal access to forecasts, sales data, and plans.					
SCP4	Our company builds up the reward structure to align the incentives of supply chain partners.					
SCP5	Our company develops contingency plans to increase supply chain stability.					
Please indicate the timeliness with which your company can engage in the following activities.						
2. Supply Chain Alertness						
SCA1	Identify technologies for supply chain management that increase supply chain visibility.					
SCA2	Track structural changes (i.e. structural shifts in the market caused by economic progress, political and social changes, demographic trends and technological advances)					
SCA3	We detect threats to supply networks					
SCA4	We detect sudden changes in demand					
SCA5	We detect unexpected changes in the physical flows throughout the supply chain.					
Please indicate the quickness speed/quickness (degree of responsiveness) with which your company can engage in the following activities.						
3. Supply Chain Agility						
SAG1	We reconfigure supply chain resources to respond to the sudden changes in supply/demand.					
SAG2	We adapt supply chain processes to reduce lead time					
SAG3	We adjust supply chain processes to increase (the ratio of) in time delivery.					
SAG4	We streamline supply chain processes to reduce non-value added activities.					
SAG5	We adapt supply chain processes to reduce new product development cycle time.					