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Effects of product and supplier criticality on resilience capabilities: An empirical analysis of a global supply chain

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Abstract: From resilience perspective, it is important for supply chains to have multiple suppliers in order to maintain a high level of operational performance. On the contrary, keeping multiple suppliers are expensive from purchasing perspective, because, large amount of internal resources are required to maintain numerous suppliers. Moreover, some products may only have a sole source of supply. Against the backdrop, it is important for supply chains to understand, how, different products and supplier compositions affect different resilience capabilities. Hence, drawing from the literature of supply chain resilience, first, conceptual linkages among product criticality, supplier criticality and resilience capabilities are derived. Second, data from four plants of a global manufacturing organization with different supplier and product compositions are collected. Finally, hypothesized relationships are tested by using parametric statistical tests. The empirical data indicate that product and supplier criticality affect different capabilities of supply chain resilience. Theoretical contribution of this research is the conceptual model that is derived from synthesizing the existing literature of supply chain resilience. Practical contribution is the enhanced understanding of the effects of product and supply criticality on different resilience capabilities.

Keywords: Supply Chain Resilience, Supply Disruption, Business Impact, Time to Recovery, Empirical Study

JEL codes: L23; L14

1. Introduction

In March 2012, the auto industry was rocked by a shortage of a specialty resin called nylon 12, used to manufacture fuel tanks, brake components, and seat fabrics. This was attributed to the fact that the key supplier, Evonik, had experienced a devastating explosion in its plant in Marl, Germany. It had taken Evonik six months to restart production, causing downstream production facilities of Ford and other major automakers to be severely disrupted for that period of time (Simchi-Levi et al. 2014)

The above is an example of the criticality of suppliers of manufacturing organizations sourcing globally. Referring to the same disruption, former Executive Director of Purchasing at General Motors Zamjahn stated:

"The supply situation for nylon 12 is often described as diamond shaped, referring to the point at the bottom with one supplier controlling up to as much as 75% of the feedstock. It's very hard to identify where those types of situations are located because suppliers don't want to disclose that they have a market locked up" (Smock 2012).

Because of the difficulty in identifying such events, the solution sought by the automakers for this particular incident was to push their suppliers to develop an alternative to Nylon 12 that could fit their requirements. Furthermore, the impact of sudden shortage of Nylon 12 was tackled by stable vehicle inventories maintained by the automakers.

“From our standpoint, we've seen no production disruptions and have developed some alternative materials for specific applications,”

- Frank Buscemi, Marketing and Communications Director, TI Automotive, a global supplier of fluid storage (Smock 2012).

“*As of now, any potential impact from the PA-12 resin plant fire has been minimal if any. Vehicle inventory is stable and widespread shortages have ben negated*”.

- Schuster, Senior Vice President, Forecasting at LMC Automotive (Smock 2012)

The above case exemplifies two vulnerabilities of modern supply chains: globalization and outsourcing. Globalization has transformed single organizations into a web of suppliers in order to reduce cost as well as focus on core competencies. One of the greatest implications of such transformation is the increasing number of supply disruptions, occurring from countless number of sources. Thus, a growing concern is managing the risk associated with these suppliers that can reduce supply chain performance significantly. While traditional risk management practices rely proactively on identifying, assessing and treating risk, resilience scholars, on the contrary, argue that building resilient supply chains will enable organizations to survive, adapt and grow in the face of turbulent changes (Sheffi & Rice 2005; Fiksel 2006; Pettit et al. 2013).

Furthermore, focus on core competencies and cost efficiency have driven organizations to the path of outsourcing of product, material, parts, components from suppliers located at different corners of the world. Present day global sourcing organizations are more reliant on suppliers than ever before. This increased reliance on suppliers placed at least two requirements on purchasing organizations: (1) understanding the supply base in terms of how critical the suppliers are; (2) understanding internal capabilities in terms of how critical their own products and services are. Therefore, identifying critical suppliers are important for devising mitigation strategies in the event of supply disruptions. For instance, for a sole source supplier, there are no other sources. Hence, only option for such products is to redesign the product to have parts and components that have many suppliers instead of only one. Similarly, recognition of critical products can facilitate decisions such as how much inventories are required to be maintained for a particular product, so that, loss in profitability can be avoided if a supply disruption has been experienced.

To summarize, in order to tackle the effect of supply disruptions caused by globalization and outsourcing, it is essential for supply chains to become resilient. However, it is also vital for organizations to know how different product and supplier compositions can affect supply chain resilience so that proper strategies can be adopted to ensure resilience. Though, many scholars proposed normative guidelines on how organizations can build resilient capabilities (Sheffi & Rice 2005; Fiksel 2006; Jüttner & Maklan 2011; Pettit et al. 2013), there is a significant gap in literature, with regards to how these capabilities are affected by different levels of product and supplier criticality. Moreover, several scholars have highlighted need for empirical research on supply chain resilience (Blackhurst et al. 2011). Consequently, the purpose of this paper is twofold. Establish conceptual linkages among product criticality, supplier criticality and supply chain resilience as well as empirically explore relationships among them.

Hereafter, this paper is structured into three parts. In the first part, the literature is reviewed in order to define product and supplier criticality to conceptualize their proposed relationships with supply chain resilience. Next, data of four manufacturing plants of a global supply chain are analyzed to explore the proposed relationships between the concepts in practice. Finally, in the third part, findings and implications of the research are discussed.

2. Literature Review

2.1. Supplier Criticality and Product Criticality

Different literature streams defined supplier criticality in different ways. There exists a large body of practitioners' literature that views supplier criticality from business continuity perspective. For instance, Goulet, (2009) defined critical suppliers as "a supplier that an organization cannot do business without". On a similar note, Volatier et al. (2009) tagged critical suppliers as those that will have the greatest impact on the business. Wicks (2011) defined the critical supplier in following way:

> *"Those suppliers that support or provide key resources, processes, activities, products or services, whose failure (or disruption in ability to supply) would have the most significant short and medium term impact on the success or survival of a business."*

Similar to the definition provided by Wicks (2011), purchasing and supply management (PSM) literature stream recognized a critical supplier as the supplier delivering products and processes vital to the organization (Nellore & Söderquist, 2000; Caniëls & Gelderman, 2007; Lin et al., 2009). The vital or critical products are referred as unique products with high technical sophistication or R&D investments (Kraljic 1983) or products with high profitability (Hallikas et al. 2005; Caniëls & Gelderman 2007). Products that are of either high value or high volume or both will normally have high profitability and thus considered critical for the organization. Critical products are also defined as products that have less part commonality with other products and as a result modular design for such products is not possible (Goyal &

Netessine 2011). Moreover, products that are difficult to source are also termed as critical (Pettit et al. 2013).

As it is evident from above discussion, while practitioners' literature views critical supplier as the supplier who has the greatest impact on the business, PSM, literature highlights the importance of product criticality to define supplier criticality.

Contrary to these views, supply chain risk management literature, differs in defining supplier criticality. In this literature stream, critical suppliers are the suppliers who offer the greatest risk for the purchasing organization. One of the aspects of this risk is related to number of supplier sources available for a product (Wei & Wang 2010). If there exists only one source for a product in the entire planet, the supplier is defined as a sole source and offers greatest amount of risks and consequently considered as highly critical for the purchasing organization. Similarly, products that have one or several alternative sources are slightly less critical than a sole source product but more critical than products that have dual or multiple sources (Yu et al. 2009).

From the above discussion of the definitions of supplier and product criticality, it can be concluded that supplier criticality and product criticality are interdependent. When a critical supplier is defined as a supplier supplying critical product, supplier criticality depends on product criticality. On contrary, when a product has a critical supplier, for instance, in the case of sole sources for which no alternative source exists, product criticality is dependent on supplier criticality.

2.2. Supply Chain Resilience

Christopher & Peck (2004) defined supply chain resilience as "the ability of a system to return to its original state or move to a new, more desirable state after being disturbed". In similar fashion, Sheffi & Rice (2005) defined resilience as the firm's ability to recover from disruptive events. While the some authors defined resilience in more reactive manner, Ponomarov & Holcomb (2009) on contrary, put forward proactive aspect of resilience and described resilience as "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining business continuity at desired level". Realizing this shift in resilience definition, Jüttner & Maklan (2011) distinguished between two forms of resilience: adaptive and formative resilience. Adaptive resilience are related to reactive aspects of resilience, such as, "responsiveness" and "recovery"; whereas, formative resilience are considered as "antecedents" of supply chain resilience, and consequently, related to proactive aspects of resilience, such as, flexibility and redundancy.

The fundamental difference between proactive and reactive aspects of resilience is that, proactive views focus on building up capabilities before a disruptive event, while reactive views concentrate more on getting back to the original state of performance after the disruptive event. To exemplify, proactively, inventory can be stored at various nodes of supply chains, such as, at a supplier plant as raw materials, in manufacturing plant as in process inventory, in retail stores as finished goods inventory to ensure that supply chain will continue to perform at a desired level even after a disruptive event. Stockpiling such inventories will create redundancy in supply chain and will allow necessary time to recover from the disruption (Sheffi & Rice 2005).

Similarly, quick reaction to a disruptive event is also crucial for minimizing performance damages from disruptions. For instance, citing the example of Nokia's and Ericsson's responsiveness to a sub-supplier disruption, Chopra & Sodhi (2004) noted that, it was the slow response of Ericsson, that ultimately drove them out of cell phone business in 2000.

From the above discussions of proactive and reactive resilience, it can be argued that resilience capabilities can be built into the supply chain by activities, such as, keeping inventories at different nodes of supply chains. However, to check whether such storing of inventories has made the organization resilient or not, one has to look into indicators through which resilience can be observed or measured. This conceptualization of supply chain resilience is also in line conceptualization of resilience is in engineering literature

"We can only measure the potential for resilience but not resilience itself.

—David Woods (2006, p. 348)

To exemplify, recovery is considered as one of the capabilities of resilience and defined as the ability to return to normal operation state rapidly (Ponomarov & Holcomb 2009; Pettit et al. 2013). Recovery as evident from the above definition has a time dimension attached to it, which is, time to recovery. Time to recovery is defined as the time it would take for a particular node (e.g. suppliers, manufacturers, retailers) to be restored to full functionality after a disruption (Simchi-Levi et al. 2014). While recovery is hard to measure, time to recovery after a disruption, on contrary, is an observable parameter that can be measured readily.

However, time to recovery is not the only measurable variable that could indicate resilience. Pettit et al. (2013) postulated and tested empirically that by improving resilience, performance volatility can be reduced. Again, if inventories are stockpiled in order to impart resilience, it will not only allow supply chains the required time to recover from the disruption but also will facilitate to continue at a desired level of performance after the disruption. Therefore, by representing performance drop by a quantifiable variable, such as, business impact from a disruption, resilience of the organization can be indicated. The more resilient the organization is, the less it would face the business impact.

2.3. Supplier criticality, product criticality and resilience:

Supplier criticality in resilience literature is closely linked with flexibility in sourcing, which is defined as one of the capability factors of resilience (Pettit et al. 2013). If there is only one source to choose from, flexibility in sourcing decreases, so does the resilience (Burke et al. 2007; Wei & Wang 2010). Consequently, single sourcing will make the organization less resilient than dual sourcing or multiple sourcing (Yu et al. 2009). Therefore, supplier criticality will have a negative impact on resilience. The more critical the supplier is, the less resilient the organization is.

No matter how the product criticality is defined, organizational resilience will be high for a less critical product than a critical one. The rationale is that for the critical product a high level of inventory is required to be maintained. While sufficient inventory increases resilience, too much inventory may decrease flexibility of the organization, and thereby, make the organization less resilient (Sheffi 2005; Lodree Jr & Taskin 2007). However, because of the interdependency between supplier and product criticality, the combination of critical suppliers and critical products will also affect resilience in a negative way.

Figure 1 summarizes the literature review by providing an illustration of the proposed relationships between supplier criticality, product criticality and resilience. However, resilience is a multi-dimensional construct and is not directly measurable (Spiegler et al. 2012), therefore, it would be difficult to observe the effects of product and criticality on resilience, if, it is kept as a holistic construct. For this reason, the construct of resilience is conceptualized as a construct made of three variables:

inventory maintained, time to recovery and business impact. Figure 2 depicts the new construction of resilience and its relationship with product and supplier criticality. The rationale behind including these three variables to define the resilience construct is twofold: (1) All these variables are measurable, concrete variables and not abstract concepts; (2) these variables altogether capture the proactive and reactive aspects of resilience. For instance, keeping safety stock is a strategy for building resilience proactively in order to minimize the negative impact of supply disruption (Christopher & Peck 2005; Sheffi & Rice 2005; Spiegler et al. 2012). On contrary, time to recovery and business impact represents the reactive aspects of resilience as these values can only be observed after a disruptive event. If recovery time is short, it indicates that the organization is more resilient. Similarly, for a resilient organization the business impact from a disruption will be small.

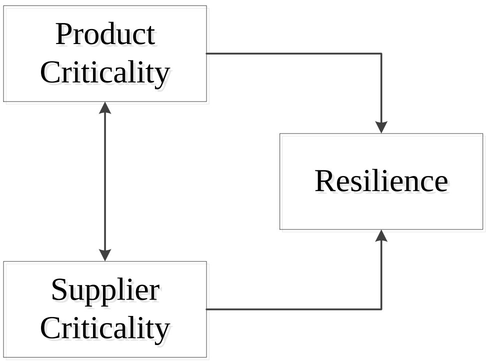

Figure 1: Relationship between product criticality, supplier criticality and resilience

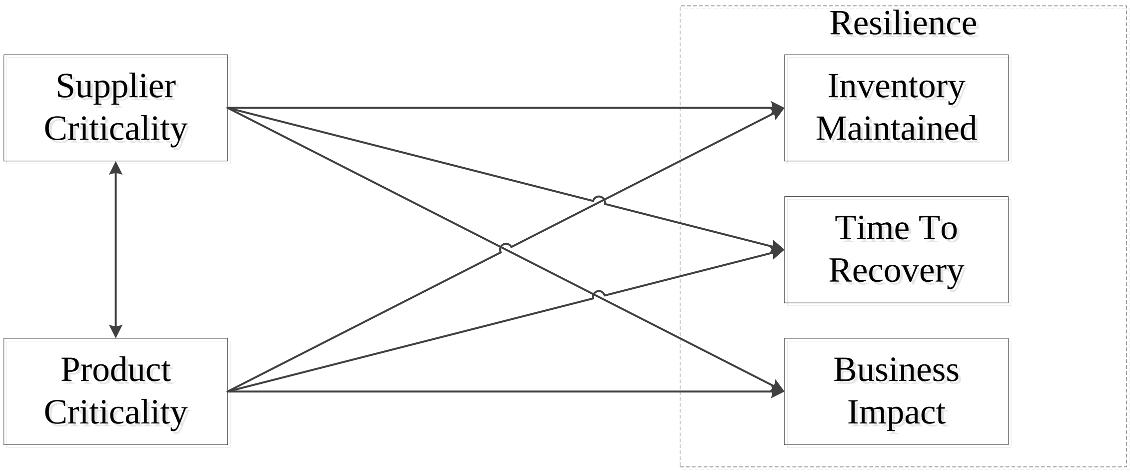

Figure 2: Relationship between product criticality, supplier criticality and resilience variables

The relationship with supplier criticality, product criticality and these three resilience variables are hypothesized as follows:

(1) Product criticality and supplier criticality are interdependent. A supplier is critical because it serves a critical product. In similar vein, a product is critical because it is supplied by a critical supplier. In other words, a critical product will always have a critical supplier and a critical supplier will always serve a critical product.

(2) Resilience variables will vary significantly for different product types. In other words, mean values of resilience variables will be significantly different for critical products than non-critical ones.

(3) Similarly, for critical suppliers, mean values of resilience variables will be significantly different than that for non-critical ones.

3. Methodology

3.1. Definitions of the empirical variables

- ❒ Supplier criticality is defined empirically by number of available suppliers for a product or by sourcing strategies. Therefore, sole sources are considered to be more critical than that of single sources. Similarly dual sources are considered to be less critical than single sources.
- ❒ Product criticality is defined by their profitability, which is calculated by ABC analysis. Therefore, both high value and high volume product are considered as critical.
- ❒ Inventory maintained is represented by the number of months of inventories that are kept for the different product types as finished goods inventory.
- ❒ Time to recovery is the time it takes to establish an alternate source of supply and return to full operational level after a disruptive event. These values are also represented in months
- ❒ Business Impact values are calculated by multiplying sales for a product category with the percentage of product delivered by a supplier.

3.2. Data collection

In order to empirically explore the relationships between product criticality, supplier criticality and supply chain resilience, data of the conceptualized variables were collected from four plants of a global manufacturing organization. Having four units from the same company are deemed appropriate to reduce potential extraneous variation (Eisenhardt 1989). Data collection was done by the insurance provider of the company. People from the insurance company involved in the data collection phase were interviewed by one of the authors as well as reports generated from the business impact analysis were gathered. Insurance provider was contacted several times to resolve confusions about the collected data. Total sample size was 69 cases where each case represented a particular combination of product and supplier type.

3.3. Characteristics of the data:

The plants were different in terms of location, size, number of key products, and number of suppliers. Demographic characteristics of the plants are presented in table 1.

Table 1: Demographic Characteristics of the plants

Demographic Characteristics	**Plant A**	**Plant B**	**Plant C**	**Plant D**
Location	Czech Republic	Malaysia	Mexico	China
Employee Number	1250	600	337	2000
Number of key products	1	3	3	3
Number of suppliers for key products	17	14	10	14

The product and supplier compositions of the plants are presented in table 2 & 3 respectively. As depicted in table 2, Plant A and Plant B had completely different product types than plant C and Plant D. Plant C and Plant D though differed in size but had similar product types.

Table 3 depicts that the plants followed mostly single sourcing strategy, with limited number of dual and sole suppliers per plant. The mean scores and standard deviations of the conceptualized resilience variables are presented in table 4. The mean scores for business impact are represented in percentage values. For time to recovery as well as for inventory maintained, the mean scores are represented in months.

Table 2: Product compositions at different plants

Product Types	**Plants**				**Total**
	Plant A	**Plant B**	**Plant C**	**Plant D**	
Product 1	16	0	0	0	16
Product 2	0	12	0	0	12
Product 3	0	16	0	0	16
Product 4	0	5	0	0	5
Product 5	0	0	1	4	5
Product 6	0	0	1	6	7
Product 7	0	0	4	4	8
Total	16	33	6	14	69

Table 3: Supplier compositions at different plants

Supplier Types	**Plants**				Total
	Plant A	**Plant B**	**Plant C**	**Plant D**	
Sole Suppliers	5	1	0	1	7
Single Suppliers	11	26	6	13	56
Dual Suppliers	0	6	0	0	6
Total	16	33	6	14	69

Table 4: Mean and Standard Deviation values of resilience variables across different plants

Resilience Variables	**Plant A (n=16)**		**Plant B (n=33)**		**Plant C (n=6)**		**Plant D (n=14)**	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Business Impact (percentage)	5.42	7.58	3.03	4.14	13.19	18.60	7.12	6.53
Time to recovery (months)	8.38	2.96	6.27	4.29	3.33	1.63	1.36	0.50
Inventory maintained (months)	1.01	0.49	1.61	0.56	2.67	1.86	0.63	0.32

3.4. Data Analysis

3.4.1 Interdependency of supplier criticality and product criticality

To check the interdependency, between product criticality and supplier criticality, a cross tabulation of these two variables was created. Relative criticalities among products were found by measuring each product's impact on business. Furthermore, supplier criticality of each product was established by weighing the type of sources available for each product. The result of the analysis is presented on table 5.

Values from table 5 indicate that our hypothesis of interdependency of supplier criticality and product criticality does not hold i.e. a critical product does not always have a critical supplier and a critical supplier does not always serve a critical product.

Only one product (product 1: product criticality = 23.75% and supplier criticality = 26.62%) out of 8 product types were both supplier and product critical at the same time. Product 4 (product criticality = 2.02% and supplier criticality = 7.19%) and product 5 (product criticality = 9.12% and supplier criticality = 7.19%) are noncritical in terms of both product and supplier criticality. Product 2, 5 & 7 are either critical in terms of business impact or critical in terms of supplier.

Table 5: Results of the analysis of interdependency of supplier criticality and product criticality

	Product types							**Total**
	Product 1	**Product 2**	**Product 3**	**Product 4**	**Product 5**	**Product 6**	**Product 7**	
Product Criticality	23.73%	20.20%	5.11%	2.02%	9.12%	31.88%	7.95%	100%
Supplier Criticality	26.62%	13.67%	23.02%	7.19%	7.19%	10.07%	12.23%	100%
Sole	5	0	1	0	0	0	1	7
Single	11	7	14	5	5	7	7	56
Dual	0	5	1	0	0	0	0	6
Total	16	12	16	5	5	7	8	69

3.4.2 Relationships between product criticality and resilience variables

The hypotheses regarding product criticality and resilience variables were that for critical products mean values of resilience variables would be significantly different than that of non-critical ones. To test those hypotheses, one way analysis of variance tests were performed for three resilience variables. Results were in consistence with our hypothesized relationships and showed that the effect of product criticality was significant for all three variables. For inventory maintained, results were $F(6, 62) = 3.55$, $p = .004$. Post hoc analyses using Tukey HSD test indicated that mean score for product 4 ($M = 2.2$, $SD = .45$) was significantly different from product 6 ($M = .68$, $SD = .07$). Values of inventory maintained did not differ significantly for any other products.

For business impact, results were $F(6, 62) = 4.13$, $p = .001$. Post hoc analyses using Tukey HSD test indicated that mean score for product 6 ($M = 16.63$, $SD = 16.33$) was significantly different from product 1 ($M =5.42$, $SD = 7.58$), product 2 ($M =6.15$, $SD = 5.62$), product 3 ($M =1.17$, $SD = .79$), product 4 ($M =6.66$, $SD = 6.09$). Product 6 did not differ significantly only with product 5 ($M =1.47$, $SD = 1.39$).

For time to recovery, results were $F(6, 62) = 6.84$, $p = .000$. Post hoc analyses using Tukey HSD test indicated that mean score for product 1 ($M = 8.37$, $SD = 2.96$) was significantly different from product 5 ($M =2.00$, $SD = 1.22$), product 6 ($M =1.57$, $SD = .79$), product 7 ($M =2.25$, $SD = 1.75$). Similarly, mean score for product 2 ($M = 7.96$, $SD = 6.35$) was significantly different from product 5 ($M =2.00$, $SD = 1.22$), product 6 ($M =1.57$, $SD = .79$), product 7 ($M =2.25$, $SD = 1.75$). Mean scores for Product 3 ($M =7.95$, $SD = 6.35$), and 4 ($M =5.16$, $SD = 2.27$), did not differ significantly with any other product.

3.4.3 Relationships between supplier criticality and resilience variables

The hypotheses regarding supplier criticality and resilience variables were that for critical suppliers mean scores of resilience variables would be significantly different than that of non-critical ones. To test those hypotheses, again one way analysis of variance tests were performed. Results were not fully consistent with our hypothesized relationships and showed significant effects of supplier criticality only for time to recovery variable with F (2, 66) = 6.88, p = .002. Post hoc analyses using Tukey HSD test indicated that mean score for sole suppliers (M = 10.42, SD = 4.16) was significantly different from single suppliers (M = 5.08, SD = 3.92) and dual suppliers (M = 3.66, SD = .93). However, mean score for single suppliers and dual suppliers did not differ significantly with each other. Furthermore, no significant effect of supplier criticality on inventory maintained F (2, 66) = .165, p = .85 and business impact F (2, 66) = .39, p = .673 variables were found.

4. Discussion of the results

The objectives of this paper were to establish conceptual linkages among product criticality, supplier criticality and supply chain resilience as well as empirically explore the relationships among them. Hence, the following discussions of the results are structured along the three hypothesized relationships: first, the relationship between product criticality and supplier criticality, second, the effects of product criticality on three resilience variables, third effect of supplier criticality on the resilience variables.

4.1. Interdependency of supplier criticality and product criticality

The empirical data failed to provide support for the interdependency between supplier and product criticality. It means not all the products that are critical for organization have critical suppliers also. This result has great theoretical and practical implications. PSM literature suggests identifying key products and processes in order to recognize key suppliers for an organization. The primary objective for such exercise is either to segment suppliers for planning sourcing strategies/ relationship strategies (Kraljic 1983; Caniëls & Gelderman 2007; Schoenherr et al. 2012; Rezaei & Ortt 2013; Imanipour et al. 2012) or to reduce the supply base (Choi & Krause 2006; Handfield & Nichols 2004; Nam et al. 2011; Sarkar & Mohapatra 2009). If supplier criticality is independent of product criticality as suggested by the empirical data, it means that a supplier can be critical for its own reasons. For example, if it is a sole supplier of a particular product and produce 75% of the world's production for that product, such suppliers in the supply chains are required to be recognized as critical suppliers irrespective of their profit impact on business. Hence, a part for which the contribution to the profit impact is very small could still be critical because of the presence of such suppliers in its supply chain. Therefore, relying only on key product and process analysis to identify the critical suppliers might bring erroneous results. Consequently, supply chains will continue to face supply disruptions because of failing to detect such critical suppliers in the supply chain. The argument that most scholars posit to highlight the importance of identifying key products for identifying critical suppliers is the sheer number of parts for some final product such as automobiles (Choi & Hong 2002; Choi & Krause 2006; Imanipour et al. 2012). Hence, considering only key products rather than all products (which can be as high as 40,000 parts for automobiles), reduces the work load for key supplier identification exercise. However, as suggested by most authors in resilient literature, in order to avoid unexpected supply disruptions or to build resilient supply chain, critical suppliers in the supply chains are required to be identified (Sheffi & Rice 2005; Wicks 2013; Lin et al. 2009), even for products that are not critical in terms of profit impact.

4.2. Effects of product criticality on resilience variables

4.2.1 Effects of product criticality on Inventory Maintained scores

In consistent with the hypothesized relationship, product criticality was found to significantly affect inventory maintained scores. The post hoc test for inventory maintained variable showed significant difference in mean scores for product 4 and product 6. From table 5 it can be seen that product 4 is a non-critical product relative to product 6 in terms of business impact and supplier criticality. Therefore, the results suggest that for critical products inventory levels are different than that for non-critical products. In other words, having critical products has implications on how redundant organization needs to be in terms of maintaining an appropriate inventory level. This finding provides justification for simplifying product design and/ or developing modular designs in order to avoid risk of supply disruptions, and become more resilient(Allred et al. 2011; Chaudhuri et al. 2013).

4.2.2 Effects of product criticality on Business Impact scores

Empirical data provided support for the effect of critical products on business impact scores i.e. for a critical product business impact score was significantly different than that of a non-critical product. Post hoc results revealed that mean scores of product 6 was significantly different from all other products except product 5. The reason for such result is revealed from Table 5 which shows that 6 had the highest business impact in comparison to all other products. Business impact in this paper is considered to capture the reactive aspect of resilience in case of a supply disruption. Hence, an important practical implication of this finding is, whenever, a prioritization of resources is required, a concentrated focus on the product that have greatest impact on business, will make organization more resilient than focusing on a noncritical product.

4.2.3 Effects of product criticality on Time to Recovery scores

In accordance with the conceptual link, times to recovery scores were also found to be significantly different for different product criticalities. The post hoc test for time to recovery scores showed product 1 and product 2 were significantly different from products 5, 6 and 7. From table 5, it can be observed that both product 1 and 2 are high in both supplier and product criticality in comparison to other products. Time to recovery scores in this article represent the amount of time required to establish an alternative source of supply. Hence, products that are critical both in terms of the business impact and supplier are found to be different than that of products that are critical either in terms of supplier or business impact. The implication of this finding is that recovery times for critical products would most probably be higher than that of a non-critical one, because, they have high business impact as well as critical suppliers. Therefore, such products need greater attention from organization aspiring to become resilient.

4.3. Effects of supplier criticality on resilience variables

4.3.1 Effects of supplier criticality on Inventory Maintained scores

In contrast with the hypothesized relationship, inventory maintained scores did not differ significantly for supplier criticality. The result indicates that even if a product is sole sourced, inventory maintained values are not different than that of a dual source. In other words, how much inventory organization maintains is not affected by the criticality of the supplier. This result has two plausible explanations: the plants from which the data were collected, did not take consideration for supplier criticality while setting the safety stock for a particular product; it is not needed to take consideration for supplier criticality to set the inventory level for a particular product. However, some scholars suggest using a combination of inventory buffer and sourcing strategies to be more resilient (Burke et al. 2007; Yu et al. 2009) which goes against the second explanation. Therefore, it is very much likely that inventory maintained scores gathered for this paper, did not account for supplier criticality appropriately.

4.3.2 Effects of supplier criticality on Business Impact scores

Empirical data did not provide support for effect of supplier criticality on Business Impact Scores. Business impact score for a product that had sole source did not differ significantly from a product that had single source. In other words, regardless of the supplier criticality, business impact scores were both high and low. This means a dual supplier has same potential to affect the business as much as a sole supplier. The managerial implication for this result is, even with a dual sourcing strategy, organization may not become as much resilient as it wishes to be.

4.3.3 Effects of supplier criticality on Time to Recovery scores

In accordance with the hypothesized relationship, empirical data provided support for the effect of supplier criticality on time to recovery values. Post Hoc test results suggested that the time to recovery scores differed significantly between sole and single source suppliers as well as between sole and dual source suppliers. However, no significant difference in mean scores of time to recovery was observed between single and dual source suppliers. The possible explanation for this result is if something happens to a sole source supplier, the only available option for the manufacturing organization is to find an alternative for the "unavailable material or parts". This can be achieved either by redesigning the product which eliminates the need of the "out of supply" material or by utilizing suppliers to develop an alternative material for the "out of supply" material (Simchi-Levi et al. 2014). On contrary, if something happens to a single source supplier, the time to recovery will depend on the time it takes to find and source from an alternative supplier. As a consequence, empirical data revealed significant difference in mean scores of time to recovery values between single and sole suppliers. Similarly, in case of dual source suppliers, time to recovery should also be significantly different than that of a single source supplier. But empirical data did not provide support for this conclusion. Possibly because even though the organization decides to pursue a dual sourcing strategy, the capacity of the dual sources may be different. Therefore, it may not be possible to retrieve the lost volume from the other supplier. Consequently, organization may still need to find an alternative supplier even for the products that are dual sourced. The managerial implication of the result is, while practicing dual sourcing strategy for a product, capacities of the dual sources are also required to be checked in order to be truly resilient from supply disruptions.

5. Conclusion

The purpose of this paper was to establish conceptual linkages among product criticality, supplier criticality and supply chain resilience and then to explore these relationships empirically. The rationale behind this purpose was to understand the effects of product and supplier criticality on resilience so that appropriate strategies could be devised to make organizations resilient against supply disruptions. The research carried out to satisfy the aforementioned purpose has several theoretical and managerial implications. First, the empirical data provided support for the conceptual relationships depicted in figure 1. It means product criticality and supplier criticality affect resilience. Second, empirical results also revealed no interdependency between product and supplier criticality. The implication of this result is both supplier criticality and product criticality are capable of affecting resilience independently and distinctively. Third, the degree of the effects of product and supplier criticality varies depending on the variables used to indicate resilience. The implication of this result is product criticality and supplier criticality will affect proactive and reactive aspects of resilience differently. Finally, the results reveal resilience as multidimensional as well as complex construct. Therefore, strategies regarding product and supplier criticality that can make the organization resilient require careful consideration of many aspects. Hence, normative guidelines (e.g. make system redundant/resilient with multiple sources or create redundancy by stockpiling inventories) that are found in excess in current body of resilience literature need to be revisited for their applicability in supply chain context. However, this article only scratched the surface for understanding the effects of product and supplier criticality on supply chain resilience. Moreover, this paper only dealt with limited number of variables to indicate resilience. In future, more in-depth studies are required to find out other variables that can concretely indicate the true nature of resilience in supply chain context.

References

Allred, C. R., Stanley E. F., Wallin, C. and Magnan, G. M. (2011), "A Dynamic Collaboration Capability as a Source of Competitive Advantage", Decision Sciences, Vol. 42 No. 1, pp.129–161.

Blackhurst, J., Dunn, K.S. and Craighead, C.W., (2011), "An Empirically Derived Framework of Global Supply Resiliency", Journal of Business Logistics, Vol. 32 No. 4, pp.374–391.

Burke, G.J., Carrillo, J.E. and Vakharia, A.J. (2007), "Single versus multiple supplier sourcing strategies", European Journal of Operational Research, Vol. 182, No. 1, pp. 95–112.

Caniëls, M.C.J. and Gelderman, C.J. (2007), "Power and interdependence in buyer supplier relationships: A purchasing portfolio approach", *Industrial Marketing Management*, Vol. 36, No. 2, pp. 219–229.

Chaudhuri, A., Mohanty, B., & Singh, K. (2013), "Supply chain risk assessment during new product development: a group decision making approach using numeric and linguistic data", *International Journal of Production Research*, Vol. 51, No. 10, pp. 2790–2804.

Choi, T.Y. and Hong, Y. (2002), "Unveiling the structure of supply networks: case studies in Honda, Acura, and DaimlerChrysler", *Journal of Operations Management*, Vol. 20, No. 5, pp. 469-493.

Choi, T.Y. and Krause, D.R., (2006), "The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation", *Journal of Operations Management*, Vol. 24, No.5, pp.637–652.

Chopra, S. and Sodhi, M., (2004), "Managing risk to avoid supply-chain breakdown" *MIT Sloan Management Review*, Vol. 46, No. 1, pp.52–62.

Christopher, M. and Peck, H., (2004), "Building the resilient supply chain", *International Journal of Logistics Management*, Vol. 15, No .2, pp.1-14.

Eisenhardt, K. (1989), "Building theories from case study research", *Academy of Management Review*, Vol. 14, No. 4, pp.532–550.

Fiksel, J. (2006), "Sustainability and resilience: toward a systems approach", *Sustainability: Science Practice and Policy*, Vol. 2, No. 2, pp. 1–8.

Goulet, D. (2009), "Pandemic planning and your supply", *Continuity Central*, pp. 5–6. Available at: http://www.continuitycentral.com/feature0699.html [Accessed May 24, 2014].

Goyal, M. and Netessine, S., (2011), "Volume flexibility, product flexibility, or both: The role of demand correlation and product substitution", *Manufacturing and Service Operations Management*, Vol. 13, No.2, pp.1–42.

Hallikas, J., Puumalainen, K., Vesterinen, T., and Virolainen, V. M. (2005), "Risk-based classification of supplier relationships", *Journal of Purchasing and Supply Management*, Vol. 11 No.2-3, pp. 72–82.

Handfield, R.B. and Nichols, E.L. (2004), "Key issues in global supply base management", *Industrial Marketing Management*, Vol. 33, No.1, pp.29–35.

Hollnagel, E., Woods, D. and Leveson, N. (Eds.). (2006), *Resilience engineering: Concepts and Precepts*, Aldershot, Ashgate, UK.

Imanipour, N., Rahimi, M. and Akhondi, N. (2012), "An Empirical Research on Supplier Relationship Management in Automotive Industry", *International Journal of Business and Management*, Vol. 7, No.9, pp.85–95.

Jüttner, U. and Maklan, S. (2011), "Supply chain resilience in the global financial crisis: an empirical study", *Supply Chain Management: An International Journal*, Vol. 16 No. 4, pp.v246–259.

Kraljic, P. (1983), "Purchasing must become supply management", *Harvard Business Review*, Vol. 61, No. 5, pp. 109-117.

Lin, R. H., Chuang, C. L., Liou, J. J., & Wu, G. D. (2009), "An integrated method for finding key suppliers in SCM", *Expert Systems with Applications*, Vol. 36, No. 3, pp. 6461–6465.

Lodree Jr, E.J. and Taskin, S. (2007), "An insurance risk management framework for disaster relief and supply chain disruption inventory planning", *Journal of the Operational Research Society*, Vol. 59, No.5, pp.674–684.

Nam, S.-H., Vitton, J. and Kurata, H. (2011), "Robust supply base management: Determining the optimal number of suppliers utilized by contractors", *International Journal of Production Economics*, Vol. 134, No. 2, pp.333–343.

Nellore, R. and Söderquist, K. (2000), "Portfolio approaches to procurement: Analysing the missing link to specifications", *Long Range Planning*, Vol. 32, No. 2 pp. 245–267.

Pettit, T.J., Croxton, K.L. and Fiksel, J. (2013), "Ensuring supply chain resilience: Development and implementation of an assessment tool", *Journal of Business Logistics*, Vol. 34, No. 1, pp. 46–76.

P Ponomarov, S.Y. and Holcomb, M.C. (2009), "Understanding the concept of supply chain resilience", *The International Journal of Logistics Management*, Vol. 20, No. 1, pp. 124–143.

Rezaei, J. and Ortt, R. (2013), "Supplier segmentation using fuzzy logic", *Industrial Marketing Management*, Vol.42, No.4, pp.507–517.

Sarkar, A. and Mohapatra, P.K.J. (2009), "Determining the optimal size of supply base with the consideration of risks of supply disruptions", *International Journal of Production Economics*, Vol. 119, No. 1, pp.122–135.

Schoenherr, T., Modi, S. B., Benton, W. C., Carter, R. C., Choi, T. Y., Larson, P. D., Leenders, R. M., Mabert, V. A., Narasimhan, R. and Wagner, S. M. (2012), "Research opportunities in purchasing and supply management" *International Journal of Production Research*, Vol. 50, No. 16, pp. 4556–4579.

Sheffi, Y. (2005), *The resilient enterprise: overcoming vulnerability for competitive advantage,* MIT Press Books.

Sheffi, Y. and Rice, J. (2005), "A supply chain view of the resilient enterprise", *MIT Sloan Management Review*, Vol. 47, No. 1, pp. 40–49.

Simchi-Levi, D., Schmidt, W. and Wei, Y. (2014), "From superstorms to factory fires managing unpredictable supply-chain disruptions", *Harvard Business Review*, Vol. 92, No.1-2, pp.97–101.

Smock, D., (2012), "Lessons from the Nylon 12 Supply Disruption The Numbers Behind the Nylon 12 Supply Chain", *My Purchasing Center*, Available at:
http://www.mypurchasingcenter.com/commodities/commodities-articles/lessons-learned-from-nylon-12-supply-disruption/ [Accessed November 24, 2013].

Spiegler, V.L.M., Naim, M.M. and Wikner, J. (2012), "A control engineering approach to the assessment of supply chain resilience", *International Journal of Production Research*, Vol. 50, No. 21, pp.6162–6187.

Volatier, L., Cordon, C. & Gallery, C. (2009), "Suppliers and vendors first", *Supply Business*, pp.1–10. http://www.supplybusiness.com/previous-articles/summer-2009/features/suppliers-and-vendors-first/ [Accessed April 24, 2009].

Wei, H.-L. and Wang, E.T.G. (2010), "The strategic value of supply chain visibility: increasing the ability to reconfigure", *European Journal of Information Systems*, Vol. 19, No. 2, pp.238–249.

Wicks, S. (2013), "Identifying key tier one suppliers", *Journal of Business Continuity & Emergency* Planning, Vol. 6, No. 3, pp.210–221.

Wicks, S. (2011), "An investigation into how to identify key suppliers", *Business Continuity Institute.*
Available at: www.bcifiles.com/IdentifyingKeySuppliersSteveWicksMBCI.pdf[Accessed April 24, 2009]

Yu, H., Zeng, A.Z. and Zhao, L. (2009), "Single or dual sourcing: decision-making in the presence of supply chain disruption risks" *Omega*, Vol. 37, No. 4, pp. 788–800.