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Technological capabilities and supply chain resilience of firms: A relational analysis using Total Interpretive Structural Modeling (TISM)

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ABSTRACT

Resilience, the property of supply chains to handle impending vulnerabilities and potential disruptions is becoming a success factor for modern firms. Considering the situation, a major question arises whether the companies are technologically capable of bringing supply chain resilience? Prior to take decision on implementation of supply chain risk management practices, companies need to identity their technological capabilities and its impacts on supply chain resilience. Apart from that, many of the technological capabilities are seen interrelated and have the competences to influence the other. A research in this direction could enable companies to be cognizant of their technological capabilities and to ascertain those influential capabilities for which managers should feel quintessential. A total interpretive structural modeling is used in this research to identity, interpret and acknowledge the major technological capabilities of firms that influence the resilience capabilities of their supply chains. A case evaluation of the same was also carried out in an electronics manufacturing industry. It can be inferred for the case that the most influential technological capabilities are *capability to modify supply chain design* and *planning capabilities*. A proper enhancement of these capabilities in the supply chain augments several flexibility and improves resilience capabilities.

1. Introduction

In this competitive world of globalization and vertical integration, supply chains (SC) needs to be smarter with efficient and responsive products. Along with that, the associated risks with supply networks have been exacerbated. Supply chain risk management represents proactive practices to manage risks and to effectively confront them (Colicchia and Strozzi, 2012; Manuj et al., 2014; Markmann et al., 2013; Sodhi et al., 2012). Supply chain resilience, the property by which supply chains are able to handle impending vulnerabilities and potential disruptions is becoming a success factor for all leading firms (Brandon-Jones et al., 2014; Hohenstein et al., 2015; Wieland and Marcus Wallenburg, 2013; Rajesh and Ravi, 2015; Rajesh, 2016). In this milieu, a major question arises whether the companies are technologically capable of bringing supply chain resilience. Before investing much on supply chain risk management practices, companies need to identity their technological capabilities and its influences on supply chain resilience. Companies that are too immature in their capabilities cannot implement several risk management practices altogether.

Apart from that, many of the technological capabilities are interrelated and have the competences to influence the other (Huo, 2012; Lin, 2014; Meyr et al., 2015; Williams et al., 2013). A research in this direction could possibly make companies aware of their technological capabilities and the most influential capabilities for which managers can give primary attention. A total interpretive structural modeling is used in this research to identity, interpret and acknowledge the major technological capabilities of firms that influence the resilience capabilities of their supply chains. Since the model is developed on interpretive modeling logic, the reachability matrices are constructed on relational basis and are interpreted logically. Each relation represented in the final reachability matrix designates whether the causal/ influential relations are strong enough to justify the model.

A case evaluation of the same was also carried out in an electronics manufacturing industry to identity the influence relations and the level of their technological capabilities. A relational digraph was also plotted to represent the prominent causal relations. The relational digraph is prepared on basis of the final reachability matrix and interpretive logic of the relations represented by it. Only conspicuous relations of either direct or transitive are represented in the digraph. The transitive relation logic is one of the equivalence properties for equalities and is a property common to equalities and inequalities. The model has been validated with a panel of experts and the relational digraph is updated. This research could find potential applications for operations managers to identify and relate their technological capabilities to supply chain and operational resilience.

This paper is further organized as follows; Section 2 discusses on the technological capabilities of firms that contribute to the resilience of their supply chains. Major remarks are indicated at the end of every sub- sections. Section 3 elucidates the methodology for total interpretive structural modeling and the detailed systematic analysis. A case

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evaluation of the proposed methodology was also carried out to gain practical insights. This constitutes Section 4. Section 5 discusses on the results of the case evaluation and the related remarks, which is followed by the conclusions, delimitations of the model and the scope of future works.

2. Technological capabilities contributing to SC resilience

A mature organization can design its supply chain capable of adjusting itself to fine-tune with demand fluctuations and other market turbulences. Most of the companies adopt several risk management practices, still consistent reduction of potential vulnerabilities is not perceived. This occur as the companies are either immature in their technological capabilities for bringing supply chain resilience or the companies relies too much on their capabilities to manage vulnerabilities. Both status quo are dangerous and can lead to situations of lost sales or unfulfilled demands bringing diminished reputations for firms. The major technological capabilities (TC) of firms having a challenging role in building resilience in their supply chains are as follows.

2.1. TC 1: Capability to modify SC design

Designing the supply network is a critical strategic decision needing time and efforts. The supply networks should be designed in such a way that the design changes could be incorporated into it at any stage of the supply chain (Holweg and Helo, 2014). Design should avoid any bottlenecks and the nodes must be positioned in supply network to reduce node density, node complexity and node criticality. Too many nodes placed in near vicinity increases node density and reduce network reliability. When the number of inter nodal connections increases, the network resilience decreases. Also, the nodes must be designed in a way to reduce the criticality of the design. If the number of connections of a node increases without any parallel network connections, the network design becomes critical and the vulnerability increases. *NB 1: Whether the supply chain is technologically capable of altering its network design according to demanding needs is one of the major factors influencing supply chain resilience.*

2.2. TC 2: Capability of supply flexibility

Supply chains must be designed to have good supply flexibility (Esmaeilikia et al., 2014). Single sourcing can be seen as the root cause for many supply side disruptions. Multiple sourcing is a potential alternative but this reduces the visibilities in supply chains. Information sharing with too many partners can tamper the security of the supply chain. Keeping a chief supplier and making other suppliers available in emergencies could be a possible solution. Supply flexibility can be imparted through flexible suppliers and through flexible supply contracts. *NB 2: Whether the supply side is flexible enough to handle demand fluctuations strongly favor the resilience capabilities of the firm.*

2.3. TC 3: Capability of capacity enhancements

Capacity is an essential buffer. A part of the demand fluctuations and bull whips can be managed through varying the production and distribution capacity utilizations. Capacity can be used as a buffer by utilizing the material pipelines (Hu et al., 2013). Too much capacity utilizations can create bottlenecks and too low utilizations can results in increased costs of capacities. Capacity must be carefully planned and utilized properly in a supply network. This can reduce the risk of delayed responses and postponements and the associated vulnerabilities. *NB 3: The capabilities of the firm to plan and effectively utilize its capacities have a positive influence on the resilience prospective of the firm.*

2.4. TC 4: Level of standardization

Standardizations determine the level at which the operations adhere to standard operating procedures and the level at which the products and production flexibilities are offered. Increase in level of standardized parts for products increases the production flexibility and helps in having interchangeable product assemblies. This helps in the quicker incorporation of any product design changes (Serdarasan, 2013). Also it is advantageous when there are multiple products in the markets of the same part families. Standardization levels are more for mature or technologically advanced firms. *NB 4: The capacities for process and product standardizations of the firm have a direct positive influence over the resilience of its supply chain.*

2.5. TC 5: Agile capabilities

Agility of the supply chain refers to the level of visibility and the level of responsiveness of the supply chain. Quick acting supply chains are said to have high supply chain velocities and more information sharing practices increases the visibilities of supply chains (Eckstein et al., 2015). When the supply chain operations are transparent to partners, there is an increase in the trust levels and a noticeable increase in the level of resilience. Agility is imparted through increased visibilities, enhanced velocities and better transparency of operations in supply chains. *NB 5: Technological capabilities of the firm to become more agile makes its supply chain least vulnerable to potential disruptions.*

2.6. TC 6: Collaborative capabilities

Increased information sharing practices enhances the trust among partners. This will enhance the collaborative capabilities along with opportunities for risk hedging. The supply chain can bend together rather to break at a point during times of disruptive events. The levels of collaboration depend on the nature and volume of the shared data among partners (Ramanathan et al., 2014). Collaboration can be well utilized in the planning and forecasting phase of supply chains. Increase in collaboration levels makes it easy to manage inventories in the network. *NB 6: Integrated supply chains with enhanced collaborative capabilities can reduce the associated vulnerabilities of networks.*

2.7. TC 7: Postponement capabilities

Postponement or delayed differentiation is a strategy adopted to delay the assembly of products up to a point where exact customer information are available. Postponement is usually practiced by established firms through enhanced information sharing practices (Chaudhry and Hodge, 2012). The companies that are technologically capable of adopting postponements must have customers willing to wait for their products. This could enable them to shift inventory across time. Increased level of product flexibilities along with reduced level of inventory at stages are the key benefits of postponements. *NB 7: Companies that are technologically capable of postponements can effectively utilize time buffer to handle demand fluctuations and to enhance supply chain resilience.*

2.8. TC 8: Inventory capabilities

Inventory is an immediate buffer to deal with sudden demand perturbations or bullwhips. Inventory can be in the form of raw materials, work in process or as finished goods. Inventory is always associated with holding costs (Kristianto et al., 2012). The benefits of utilizing inventories should justify the holding costs and/or obsolescence costs. Companies are recommended to improve their capabilities to take decisions on inventory for different products differently, named as strategic stocking. Capability for strategic stocking based on the product risk profiles will reduce the risks of piling of inventory. *NB 8: Strategic stocking*

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capabilities allow the firms to better manage the inventories of different products differently to achieve supply chain resilience.

2.9. TC 9: Product rollover capabilities

Product introduction and withdrawals are made silently so that the firms gain more control over product exposures. Thus silient product rollover strategies increase capabilities of the firm or its supply chain to manage demand (Sodhi and Tang, 2012). It is possible for mature firms to adopt strategies of *not to market* the introduction of new products or the end of old products. *NB 9: Capabilities for silent product rollovers allow firms to increase control over product exposures leading to better management of vulnerabilities.*

2.10. TC 10: Pricing capabilities

Companies and its supply chain must allow for the flexibility of pricing. Products with immediate demands can be compromised for higher prices and those needing considerable amount of lead times should have reduced pricing schemes. The prices should vary dynamically based on the current demands, response times, frequencies of responses and many other factors (Wu et al., 2012). Responsive pricing helps to shift production quantities across products and this also increases pricing flexibility. *NB 10: Companies that are technologically capable of implementing the dynamicity of responsive pricing could ensure product flexibilities and impart supply chain resilience.*

2.11. TC 11: Planning capabilities

Assortment planning is a process in which the products are selected and planned to maximize sales and profit for a defined period of time. Assortment plans generally take into account of operational and financial objectives to ensure proper demand fulfillments considering seasonality (Kök et al., 2015). Dynamic assortment planning improves the control over product demand and increases capabilities to handle fluctuations in demand. *NB 11: Firms that are technologically well capable with their assortment planning process could ensure demand fulfillments and reduced chances of lost sales, thereby improving supply chain resilience.*

3. Methodology

A total interpretive structural modeling (TISM) is employed to identify the prominent influential relations amongst the major technological capabilities of firms to complement their supply chain resilience. Interpretive structural modeling (ISM) is a widely used tool for establishing the prominent relations among factors (Hsu et al., 2015; Kumar et al., 2013; Mangla et al., 2014; Venkatesh et al., 2015). In ISM, the digraph interpretations are carried out at *two* levels, at the nodes and at the links. ISM generally interprets the nodes by defining the elements signifying it. However, the link interpretations are comparatively weak in ISM. Along with that, dealing with qualitative criteria is an effortful task having obscurities and vagueness. In order to overcome this, ISM is further modified to TISM. In TISM, the causal relations and its interpretations given by experts are represented by an interpretive matrix for detailed systematic analysis (Dubey et al., 2015; Jayalakshmi and Pramod, 2015; Shibin et al., 2015). The detailed *step by step* analysis is elaborated as follows;

Step 1: Identify the capabilities

The technological capabilities contributing to the resilience of the supply chain needs to be identified. The elements need to be identified through careful analysis of literature and expert reviews.

Step 2: Establish and interpret contextual relationships

The contextual relationships need to be established among the variables of interest. For instance, if technological capability *A* influences *B*, the relation should be recorded. An interpretation of the relation should also be made representing how technological capability *A* influences *B*?

Step 3: Construct direct reachability matrix

Prominent influential relations are represented by *Yes (Y)* and the least influential relations are represented by *No (N)* in the matrix. The matrix is transformed into a binary matrix (0 or 1) representing relations. This matrix represents the direct reachability matrix.

Step 4: Construct the final reachability matrix

The transitive relations are identified and are represented in the reachability matrix to construct the final reachability matrix. If there are significant relations where an attribute influences the other and the influenced attribute in turn influences another attribute, there exist relation between the *first* and the *third* attribute named as a transitive relation.

Step 5: Level partitions in the final reachability matrix

Level partition is done is carried out for the attributes to place the elements level- wise. The reachability, antecedents and the intersection elements are represented in a table. The elements in the top of the hierarchy will not reach any elements above them. Hence the reachability for the top level elements represents those elements itself and the elements in the same level if it reaches. The antecedent set consists of elements and the group of elements that help achieving it. The intersection of these *two* sets represents the reachability set itself, if the element is at the top level. The elements represented in the top level are removed and the reachability and antecedent sets are determined again. The process is iteratively continued until elements at all levels are determined.

Step 6: Develop the digraphs

The prominent relations in the final reachability matrix are represented in the digraphs. The elements are arranged level- wise and the most influential relations are plotted in the digraphs. The process is conducted on basis of an interpretive logic from the knowledge base of the influential relations.

Step 7: Validate the digraph and construct the TISM model

The represented relations in digraphs are to be validated using a panel of experts. Most prominent relations represented in digraphs are assessed on an influential scale varying from *one* to *five* representing a least prominent relation to a most prominent relation. Average scores for each elemental relationship are determined. A threshold for the values is also fixed where the average score for each influential relation if falls below the threshold are removed to form the final digraph demonstration. Each relation in the digraph is interpreted logically to build the TISM model.

4. Case evaluation

A case evaluation of the proposed model has been conducted in an Indian electronic manufacturing industry, *ABC*. The company produces and markets electronic gadgets especially smart phones and tablets. They have captured market attention with innovative products in reasonable price tags. *ABC* expects a peak increase in its market share by introducing *two* major products in their smartphone segments. The company desires to assess their risk profiles and to expand their risk management practices. Since markets are volatile, having flexibility is the only way to survive in the market and to increase their shares.

Before expanding their risk management system, the company needs to know whether they are technologically capable of adopting and expanding practices for supply chain risk mitigation. This research was conducted to assess the major technological capabilities of the company and to identify the most influential technological capabilities of

Table 1
Technological capabilities of firms and its relation to SC resilience.

Ref no.	Technological capability	Relevant literature	Relation to SC resilience
TC 1	Capability to modify SC design	Waller and Fawcett, 2013; Huang and Goetschalckx, 2014	Capability to incorporate design changes to impart network resilience
TC 2	Capability of supply flexibility	Chiang et al., 2012; Jayant and Ghagra, 2013	Having flexible supply base and flexible supply contracts reduces chances of supply side disruptions
TC 3	Capability of capacity enhancements	Liu et al., 2013; Georgiadis and Athanasiou, 2013	Capacity can be used as a buffer against demand side fluctuations, bullwhips or even disruptions
TC 4	Level of standardization	Baud-Lavigne et al., 2012; Sáenz and Revilla, 2014	Standardized products increases production flexibility and enhances resilience
TC 5	Agile capabilities	Gligor and Holcomb, 2012; Khalili-Damghani and Tavana, 2013	Capabilities to increase visibilities and velocities in supply chains reduces vulnerability
TC 6	Collaborative capabilities	Hudnurkar et al., 2014; Ramanathan and Gunasekaran, 2014	Increased sharing of information and improving the trust in relations improves risk hedging opportunities
TC 7	Postponement capabilities	Choi et al., 2012; Qrunfleh and Tarafdar, 2013	Postponement capabilities improve product flexibilities by utilizing time buffer
TC 8	Inventory capabilities	Olhager, 2013; Croson et al., 2014	Strategic stocking capabilities based on product risk profiles reduce the risks of inventory
TC 9	Product rollover capabilities	Jafarian and Bashiri, 2014; Rajesh et al., 2015	Improves product flexibilities and reduce the risks of inventory
TC 10	Pricing capabilities	Huang et al., 2012; Zhang et al., 2013	Responsive pricing capabilities enable the shift of product quantities across products
TC 11	Planning capabilities	Hübner et al., 2013; Taghavi and Chinnam, 2014	Dynamic assortment planning increases the control over product demand and mange bullwhips

ABC. The results of the proposed model could enable and enhance managerial decision making through identifying, classifying and enhancing major technological capabilities of the firm for bringing supply chain resilience. The detailed *step by step* implementation of the proposed methodology is elaborated as follows;

Step1: *Eleven* of the major technological capabilities supporting supply chain resilience were identified taking insights from a general electronic manufacturing firm as elaborated in Section 5. The technological capabilities identified, its relation to resilience and the supporting literature are detailed in Table 1.

Step 2: A group of *three* supply chain analysts were employed to study the contextual relationships among the *eleven* identified technological capabilities supporting supply chain resilience. Through brain storming, the analysts identified all potential influential relations and its interpretations.

Step 3: The potential relations are marked in the binary matrix to represent all influential relations. This forms the direct reachability matrix as shown in Table 2. Each element in the matrix represents a direct influential relation from technological capability *A* to *B*.

Step 4: From the interpretive logic, all the significant transitive relations are identified. The direct relation matrix is then updated by indicating all the transitive relations to form the final reachability matrix. The final reachability matrix is as represented in Table 3.

Step 5: Level partition is done following step 5 in Section 3 and the technological capabilities are placed level- wise indicating its influences. The reachability of the elements, the antecedents and the intersection elements were sorted at each level and the procedure is repeated as shown from Tables 4–10.

Step 6: After signifying the elements at different levels, digraphs are plotted representing most significant influence relations. The relations are identified from the final reachability matrix and the interpretive logic of the relations. Important transitive links are also recognized and represented in the digraphs. Most important transitive links and the interpretations of the relations are shown in Table 11 and constructed digraph is shown in Fig. 1.

Step 7: The constructed digraphs are validated using an expert panel of *five* supply chain analysts. Prominent relations in the digraph are rated on a scale from *one* to *five* signifying the importance of relations. *One* represents a not so important influential relation and *five* represents a most important one. Average scores were obtained and those relations satisfying an average score of *three* (60 percent) or above were retained in the digraphs and other relations were removed to obtain the final digraph representation of the TISM model. The validated model can be interpreted logically for detailed understanding each link in the digraph to form the TISM model. The validation of the relations represented in links as in digraphs is indicated in Table 12. The validated model and the digraph representing the relations are shown in Fig. 2.

Table 2
Direct reachability matrix.

	TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7	TC 8	TC 9	TC 10	TC 11
TC 1	1	1	0	1	0	1	0	1	1	1	0
TC 2	1	1	1	0	0	0	0	1	0	0	0
TC 3	0	1	1	0	0	0	0	0	0	0	0
TC 4	0	1	0	1	0	0	0	0	0	0	0
TC 5	1	1	0	1	1	0	0	0	0	0	0
TC 6	0	1	0	0	0	1	1	0	0	1	1
TC 7	0	1	0	0	1	0	1	1	0	1	0
TC 8	0	1	0	1	0	0	0	1	1	0	0
TC 9	0	0	0	0	0	0	0	0	1	0	0
TC 10	0	0	0	0	0	0	0	0	0	1	0
TC 11	1	1	1	1	0	1	0	1	0	0	1

Table 3
Final reachability matrix.

	TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7	TC 8	TC 9	TC 10	TC 11
TC 1	1	1	1*	1	1	1	0	1	1	1	0
TC 2	1	1	1	0	1	0	1	1	0	0	0
TC 3	0	1	1	0	1	0	0	0	0	0	0
TC 4	0	1	0	1	0	0	1	1	0	0	0
TC 5	1	1	0	1	1	0	0	1	0	0	0
TC 6	0	1	0	0	1	1	1	1	0	1	1
TC 7	0	1	0	1	1	0	1	1	0	1	0
TC 8	0	1	0	1	0	0	1	1	1	0	0
TC 9	0	0	0	0	1	0	0	0	1	0	0
TC 10	0	1	0	1	0	1	1	0	0	1	0
TC 11	1	1	1	1	1	1	0	1	1	0	1

* Elements in the yellow shaded regions represent transitive links
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Table 4
Intersection of reachability and antecedent sets and representation of level group 1.

Sl no.	Reachability	Antecedent	Intersection set	Level
TC 1	TC 1, TC 2, TC 3, TC 4, TC 5, TC 6, TC 8, TC 9, TC 10	TC 1, TC 2, TC 5, TC 11	TC 1, TC 2, TC 5	
TC 2	TC 1, TC 2, TC 3, TC 5, TC 7, TC 8	TC 1, TC 2, TC 3, TC 4, TC 5, TC 6, TC 7, TC 8, TC 10, TC 11	TC 1, TC 2, TC 3, TC 5, TC 7, TC 8	1
TC 3	TC 2, TC3, TC 5	TC 1, TC 2, TC 3, TC 11	TC 2, TC 3	
TC 4	TC 2, TC 4, TC 7, TC 8	TC 1, TC 4, TC 5, TC 7, TC 8, TC 10, TC 11	TC 4, TC 7, TC 8	
TC 5	TC 1, TC 2, TC 4, TC 5, TC 8	TC 1, TC 2, TC 3, TC 5, TC 6, TC 7, TC 9, TC 11	TC 1, TC 2, TC 5	
TC 6	TC 2, TC 5, TC 6, TC 7, TC 8, TC 10, TC 11	TC 1, TC 6, TC 10, TC 11	TC 6, TC 10, TC 11	
TC 7	TC 2, TC 4, TC 5, TC 7, TC 8, TC 10	TC 2, TC 4, TC 6, TC 7, TC 8, TC 10	TC 2, TC 4, TC 7, TC 8, TC 10	
TC 8	TC 2, TC 4, TC 7, TC 8, TC 9	TC 1, TC 2, TC 4, TC 5, TC 6, TC 7, TC 8, TC 11	TC 2, TC 4, TC 7, TC 8	
TC 9	TC 5, TC 9	TC 1, TC 8, TC 9, TC 11	TC 9	
TC 10	TC 2, TC 4, TC 6, TC 7, TC 10	TC 1, TC 6, TC 7, TC 10	TC 6, TC 7, TC 10	
TC 11	TC 1, TC 2, TC 3, TC 4, TC 5, TC 6, TC 8, TC 9, TC 11	TC 6, TC 11	TC 6, TC 11	

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

Sl no.	Reachability	Antecedent	Intersection set	Level
TC 1	TC 1, TC 3, TC 4, TC 5, TC 6, TC 8, TC 9, TC 10	TC 1, TC 5, TC 11	TC 1, TC 5	
TC 3	TC3, TC 5	TC 1, TC 3, TC 11	TC 3	
TC 4	TC 4, TC 7, TC 8	TC 1, TC 4, TC 5, TC 7, TC 8, TC 10, TC 11	TC 4, TC 7, TC 8	2
TC 5	TC 1, TC 4, TC 5, TC 8	TC 1, TC 3, TC 5, TC 6, TC 7, TC 9, TC 11	TC 1, TC 5	
TC 6	TC 5, TC 6, TC 7, TC 8, TC 10, TC 11	TC 1, TC 6, TC 10, TC 11	TC 6, TC 10, TC 11	
TC 7	TC 4, TC 5, TC 7, TC 8, TC 10	TC 4, TC 6, TC 7, TC 8, TC 10	TC 4, TC 7, TC 8, TC 10	
TC 8	TC 4, TC 7, TC 8, TC 9	TC 1, TC 4, TC 5, TC 6, TC 7, TC 8, TC 11	TC 4, TC 7, TC 8	
TC 9	TC 5, TC 9	TC 1, TC 8, TC 9, TC 11	TC 9	
TC 10	TC 4, TC 6, TC 7, TC 10	TC 1, TC 6, TC 7, TC 10	TC 6, TC 7, TC 10	
TC 11	TC 1, TC 3, TC 4, TC 5, TC 6, TC 8, TC 9, TC 11	TC 6, TC 11	TC 6, TC 11	

Table 6
Intersection of reachability and antecedent sets and representation of level group 3.

Sl no.	Reachability	Antecedent	Intersection set	Level
TC 1	TC 1, TC 3, TC 5, TC 6, TC 8, TC 9, TC 10	TC 1, TC 5, TC 11	TC 1, TC 5	
TC 3	TC3, TC 5	TC 1, TC 3, TC 11	TC 3	
TC 5	TC 1, TC 5, TC 8	TC 1, TC 3, TC 5, TC 6, TC 7, TC 9, TC 11	TC 1, TC 5	
TC 6	TC 5, TC 6, TC 7, TC 8, TC 10, TC 11	TC 1, TC 6, TC 10, TC 11	TC 6, TC 10, TC 11	
TC 7	TC 5, TC 7, TC 8, TC 10	TC 6, TC 7, TC 8, TC 10	TC 7, TC 8, TC 10	
TC 8	TC 7, TC 8, TC 9	TC 1, TC 5, TC 6, TC 7, TC 8, TC 11	TC 7, TC 8	
TC 9	TC 5, TC 9	TC 1, TC 8, TC 9, TC 11	TC 9	
TC 10	TC 6, TC 7, TC 10	TC 1, TC 6, TC 7, TC 10	TC 6, TC 7, TC 10	3
TC 11	TC 1, TC 3, TC 5, TC 6, TC 8, TC 9, TC 11	TC 6, TC 11	TC 6, TC 11	

5. Results and Discussions

Supply chain resilience is becoming an essential topic of discussion for managers and practioners. Resilience can be built through several risk management practices and by implementing a culture to support this. But the most important problem is whether the companies are technologically capable of affording these practices and implementing them to reality. This research has been conducted to identify, acknowledge and quantify various technological capabilities which in turn have a direct or indirect influence on the resilience capabilities of supply chains. A TISM methodology is effectively applied to elicit major influence relations and to bring out those capabilities needing imperative attentions. A case evaluation has been conducted in an electronic manufacturing industry and the following results were obtained.

From the implementation of the TISM model, it is seen that there are significant influential relations exist among the technological capabilities favoring supply chain resilience. It is noteworthy that the *capability to modify supply chain design* has a direct influence on *supply flexibility, capacity enhancements, collaborative capabilities, inventory capabilities* and the *capabilities for product roll overs*. Hence the design flexibility is a major technological capability of the company and if implemented properly can bring many other types flexibility into the supply chain.

Table 7
Intersection of reachability and antecedent sets and representation of level group 4.

Sl no.	Reachability	Antecedent	Intersection set	Level
TC 1	TC 1, TC 3, TC 5, TC 6, TC 8, TC 9	TC 1, TC 5, TC 11	TC 1, TC 5	
TC 3	TC3, TC 5	TC 1, TC 3, TC 11	TC 3	4
TC 5	TC 1, TC 5, TC 8	TC 1, TC 3, TC 5, TC 6, TC 7, TC 9, TC 11	TC 1, TC 5	4
TC 6	TC 5, TC 6, TC 7, TC 8, TC 11	TC 1, TC 6, TC 11	TC 6, TC 11	
TC 7	TC 5, TC 7, TC 8	TC 6, TC 7, TC 8	TC 7, TC 8	4
TC 8	TC 7, TC 8, TC 9	TC 1, TC 5, TC 6, TC 7, TC 8, TC 11	TC 7, TC 8	4
TC 9	TC 5, TC 9	TC 1, TC 8, TC 9, TC 11	TC 9	4
TC 11	TC 1, TC 3, TC 5, TC 6, TC 8, TC 9, TC 11	TC 6, TC 11	TC 6, TC 11	

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Table 8
Intersection of reachability and antecedent sets and representation of level group 5.

Sl no.	Reachability	Antecedent	Intersection set	Level
TC 1	TC 1,TC 6	TC 1, TC 11	TC 1	
TC 6	TC 6, TC 11	TC 1, TC 6, TC 11	TC 6, TC 11	5
TC 11	TC 1, TC 6, TC 11	TC 6, TC 11	TC 6, TC 11	

Table 9
Intersection of reachability and antecedent sets and representation of level group 6.

Sl no.	Reachability	Antecedent	Intersection set	Level
TC 1	TC 1	TC 1, TC 11	TC 1	6
TC 11	TC 1, TC 11	TC 11	TC 11	

Table 10
Intersection of reachability and antecedent sets and representation of level group 7.

Sl no.	Reachability	Antecedent	Intersection set	Level
TC 11	TC 11	TC 11	TC 11	7

The *capability for supply flexibility* is the most influenced technological capability as it is achieved as a combined result of many other capabilities and in general it cannot directly influence any other technological capabilities. This could be directly perceived from the obtained digraphs as in Fig. 2.

The *capability for capacity enhancements* has a direct influence on *supply flexibility* and the *agile capabilities* of the firm. Capacity can act as an essential buffer for increasing the flexibility, agility and hence the resilience of supply chains. When the *level of standardization* increases, the *flexibility of supply* is also enhanced. *Agile capabilities* of the firm influence the capabilities for *capacity enhancements* and *postponements*. Being agile makes the supply chain utilize their capacities efficiently and effectively and the enhanced visibilities enable the supply chain with the flexibility of postponements. Also, enhanced level of *collaboration* among partners increases the *pricing capabilities* and enhances the options for *postponements* through better information sharing practices.

Postponement capabilities in turn have a feedback influence on enhancing the *agility* of supply chains and have a direct influence on the capabilities of the supply chain to manage their *inventories*. This is due to the flexibility offered through delayed differentiations. Also, there is a direct influence on the supply chains to adopt policies for *responsive pricing*. The capability of supply chains to *manage their inventories* and the *rollover capabilities* are mutually influenced by each other. Strategic stocking decisions make it easy for the silent withdrawal of products and the silent introduction of products. The capabilities of *responsive pricing* enhance the *levels of standardization*, as there are different price segments for different products of same part families.

Dynamic assortment planning is a planning capability and it directly influences the *capacity utilizations, collaborative capabilities* and *inventory capabilities* of the supply chains. Assortment planning enhances the product sales and maximizes the profitability of the firm. This is made possible through optimizing the flow of their product assortments. Hence it regulates the proper utilization of capacities and inventories over stages. It is also seen that some of the enhanced practices such as collaborative planning forecasting and replenishments (CPFR) could enhance supply chain integration by supporting and assisting cooperative practices. From the interpretation of the TISM model, several transitive relations were found to be strong and have direct influence over the other. These transitive relations and the way in which the transitive flow occurs are explained in detail in Table 11.

6. Conclusions and scope of future works

The increasing trends for adopting risk management practices seem to be risky in many of the supply chains. Only those supply chains that are stable and well recognized can afford many of the risk management practices to make them less vulnerable. Technological capabilities of the supply chains play a pivotal role in determining whether the supply chains are able to afford many of the risk management practices to bring resilience into their supply chains. Knowing these capabilities is a primary need for achieving resilience in their supply chains. *Eleven* of the major technological capabilities that could certainly enhance resilience were acknowledged in this research. The influential relations do exist among those capabilities and is seen that some major capabilities could possibly act as a catalyst for the enhancement of other. From the results of the case evaluation, it can be inferred that the most influential technological capabilities are the *capability to modify SC design* and the *planning capabilities*. So a proper enhancement of these capabilities in the supply chain augments several flexibilities in the supply chain and also increases the capabilities of resilience in supply chains.

The research is constrained to have certain limitations. Although the capabilities were identified through careful scrutiny of the literature, some of the capabilities such as the *agile capabilities* are difficult to measure on a practical viewpoint. The research relied only on the influential relations and the ratings were assigned from group of analysts who handle the case supply chain for a long period of over *five* years. Also, the transitive relations are rather difficult to identify since the technological capabilities are measured on a larger base. The interpretive logic of knowledge base is used to get rid of this situational crisis. The research

Table 11
Interpretation of the transitive relations in digraphs.

Sl no.	Transitive link	Relation *A-B*	Relation *B-C*
1.	TC 7 - TC 4 (TC 7 - TC 8 - TC 4)	Postponement capabilities has a direct influence on inventory capabilities as it reduces the inventory and imparts flexibility	Reduced inventory and enhanced flexibility influences the level of standardization
2.	TC 9 - TC 5 (TC 9 ~ TC 2 ~ TC 5)	Product rollover capabilities improve product flexibilities of silent introduction and withdrawal of products	Product flexibility is related to agility of the supply chain. More flexible the products are, more agile the supply chain is
3.	TC 8 - TC 7 (TC 8 - TC 2 ~ TC 7)	Capabilities of the firm to manage inventories imparts flexibility to its supply chain	Supply chain flexibility increases the postponement capabilities of the firm as the level of information sharing is more
4.	TC 6 - TC 5 (TC 6 - TC 11 - TC 5)	Improvement in collaborative capabilities increases the planning capabilities, say for example: CPFR* practices	Enhanced capabilities for planning improves the agile capabilities of the supply chain
5.	TC 1 - TC 5 (TC 1 - TC 6 ~ TC 5)	Modifying the design of supply chain can be in such a way enhance its collaborative capabilities	Increase in level of collaboration improves the planning capabilities of the supply chain and hence improves its the agility

* Collaborative Planning Forecasting and Replenishments; - significant direct relations; ~ direct relation may or may not be significant, but there is strong transitivity.

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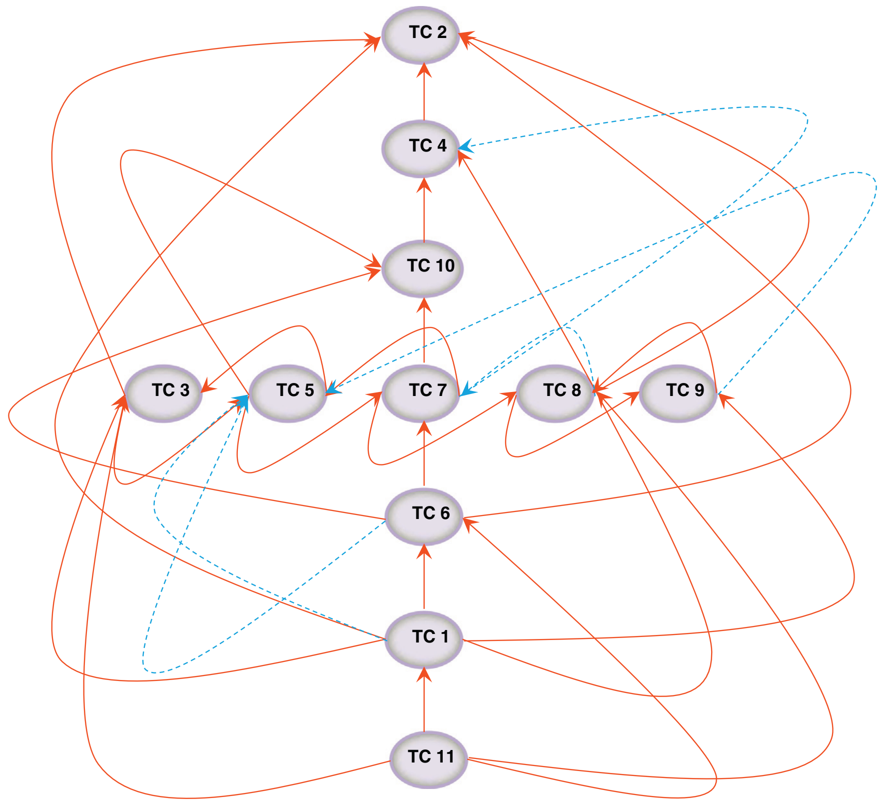

Fig. 1. Digraph representing prominent relations of the TISM model.

was conducted on the technological capabilities on a macro level and there is a need for analysis in the micro level to have a more vivid picture of the influence relations.

This research could enable managers to employ a methodological analysis for understanding their technological capabilities, identifying the most influential capabilities and propose ways to improve key

Table 12
Validation of the TISM model.

Sl No.	Relation link	Interpretation	Average score from experts	Accept/reject
1.	TC 1 - TC 2	Capability to modify SC design impacts/influences capability of supply flexibility	4.2	Accept
2.	TC 1 - TC 3	Capability to modify SC design impacts/influences capability of capacity enhancements	4.0	Accept
3.	TC 1 - TC 6	Capability to modify SC design impacts/influences collaborative capabilities	4.2	Accept
4.	TC 1 - TC 8	Capability to modify SC design impacts/influences inventory capabilities	4.6	Accept
5.	TC 1 - TC 9	Capability to modify SC design impacts/influences product rollover capabilities	3.6	Accept
6.	TC 3 - TC 2	Capability of capacity enhancements impacts/influences capability of supply flexibility	4.2	Accept
7.	TC 3 - TC 5	Capability of capacity enhancements impacts/influences agile capabilities	4.6	Accept
8.	TC 4 - TC 2	Level of standardization impacts/influences capability of supply flexibility	4.4	Accept
9.	TC 5 - TC 3	Agile capabilities impacts/influences capability of capacity enhancements	3.4	Accept
10.	TC 5 - TC 7	Agile capabilities impacts/influences postponement capabilities	4.2	Accept
11.	TC 5 - TC 10	Agile capabilities impacts/influences pricing capabilities	2.4	Reject
12.	TC 6 - TC 2	Collaborative capabilities impacts/influences capability of supply flexibility	2.6	Reject
13.	TC 6 - TC 7	Collaborative capabilities impacts/influences postponement capabilities	3.4	Accept
14.	TC 6 - TC 10	Collaborative capabilities impacts/influences pricing capabilities	4.2	Accept
15.	TC 7 - TC 5	Postponement capabilities impacts/influences agile capabilities	3.8	Accept
16.	TC 7 - TC 8	Postponement capabilities impacts/influences inventory capabilities	4.6	Accept
17.	TC 7 - TC 10	Postponement capabilities impacts/influences pricing capabilities	3.6	Accept
18.	TC 8 - TC 2	Inventory capabilities impacts/influences capability of supply flexibility	3.8	Accept
19.	TC 8 - TC 7	Inventory capabilities impacts/influences postponement capabilities	3.6	Accept
20.	TC 8 - TC 9	Inventory capabilities impacts/influences product rollover capabilities	4.8	Accept
21.	TC 9 - TC 8	Product rollover capabilities impacts/influences inventory capabilities	4.4	Accept
22.	TC 10 - TC 4	Pricing capabilities impacts/influences level of standardization	4.4	Accept
23.	TC 11 - TC 1	Planning capabilities impacts/influences capability to modify SC design	2.8	Reject
24.	TC 11 - TC 3	Planning capabilities impacts/influences capability of capacity enhancements	4.4	Accept
25.	TC 11 - TC 6	Planning capabilities impacts/influences collaborative capabilities	4.6	Accept
26.	TC 11 - TC 8	Planning capabilities impacts/influences inventory capabilities	3.4	Accept
27.	TC 1 - TC 5	Capability to modify SC design impacts/influences (in transitivity) agile capabilities	4.2	Accept
28.	TC 6 - TC 5	Collaborative capabilities impacts/influences (in transitivity) agile capabilities	3.8	Accept
29.	TC 7 - TC 4	Postponement capabilities impacts/influences (in transitivity) level of standardization	3.8	Accept
30.	TC 8 - TC 7	Inventory capabilities impacts/influences (in transitivity) postponement capabilities	4.0	Accept
31.	TC 9 - TC 5	Product rollover capabilities impacts/influences (in transitivity) agile capabilities	4.2	Accept

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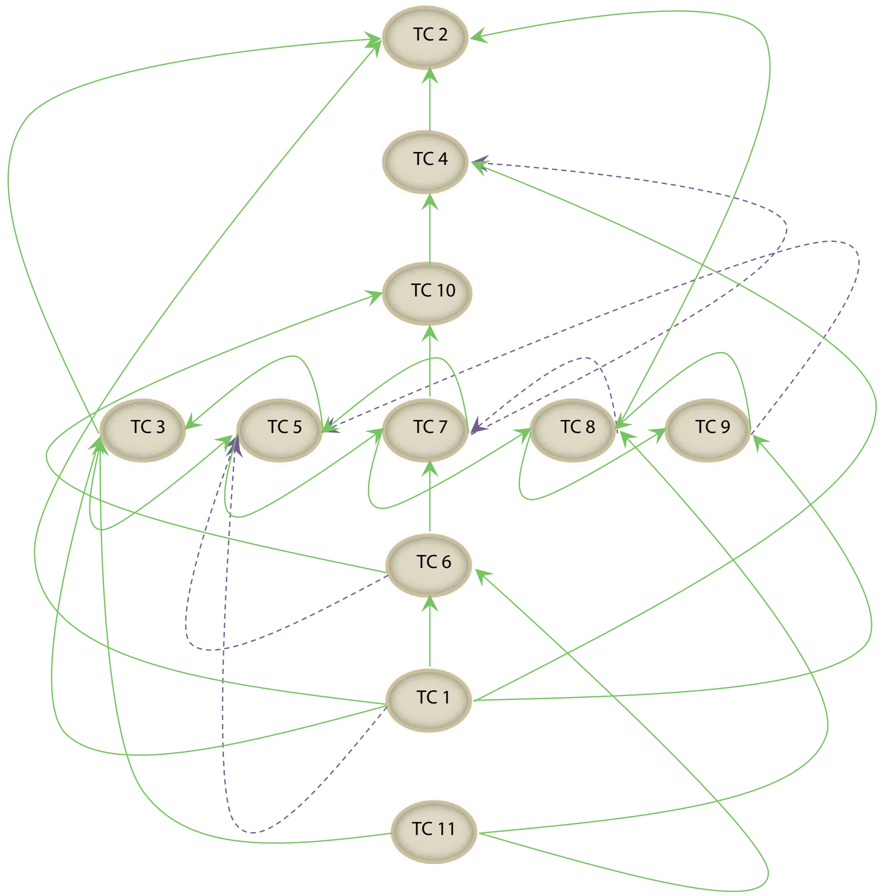

Fig. 2. Validated digraph representing prominent relations of the TISM model.

capabilities for enhanced resilience performance in their supply chains. Managers are advised to know their level of technological capabilities before bringing practices of supply chain resilience in their supply chains. This increases the success of implementation of various risk mitigation practices. It is also desirable to have a micro level analysis to identify the most influential technological capabilities at that level and is desirable to have a quantitative assessment of them. This requires strenuous efforts considering volume and time and is considered as a scope of future work. The developed TISM model and its adoption can be also be utilized to enhance the sustainability capabilities of supply chains. This is done by identifying the technological capabilities that enhances sustainability and building influential relations among them. A comparison of the results of both, helps to identify those capabilities enable the firm to create sustainable- resilient supply chains.

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