The structure of the Toyota supply network: The emergence of resilience

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Abstract
We assemble a large-scale empirical dataset that allows us to examine the local and global topology of relationships between firms in the Toyota supply network. On this basis we propose novel measures that allow us to characterise the resilience of the entire supply network. Our findings show that simple linear supply chain models are inadequate, because they neglect important lateral dependencies between suppliers. Hence, we argue that it is necessary to describe and model the supply chain as a complex network. We observe that the degree distribution for this network scales exponentially, so that disruptions at randomly chosen suppliers have little impact but vulnerability to disruptions at highly connected suppliers is significant. These potential vulnerabilities are mitigated by the network's 'small-world' structure, where the average path to any given supplier via other suppliers is very low, and the number of relations between suppliers that produce the same product types is high, especially within the Kyoho-kai supplier association. Membership of the tightly-knit Kyoho-kai supplier association is positively correlated with an increase in the number of connections that a supplier has, leading to a segmentation that favours highly connected hubs. The network also exhibits a high degree of product type redundancy, where multiple suppliers offer similar product types. When we examine product diversity along the chain we find that upper tiers show higher diversification given their vulnerability to changing customer demands. Our analysis of a unique, large-scale empirical dataset aims to move the field of supply chain management beyond stylised facts, and to demonstrate how methods from interdisciplinary work on complex networks can contribute novel insights.

1 Introduction

Growing complexity and risk implies that supply chain management needs not only to focus on measures of efficiency and profitability, but must increasingly attend to the key issue of resilience. Many commonly used definitions of resilience originate from the literature on ecological systems, and refer to the ability of a system to recover and return to its original or equilibrium state after a disturbance or perturbation (Holling 1973). A related concept is robustness, defined by the ability of a system to withstand disruptions by preserving its output. Robustness can be seen as a static property and part of resilient system, while resilience is time-related. In this paper we examine both from a topological perspective, and use the term resilience as an encompassing term, while refer to robustness only when we the context excludes resilience.

Disturbances within a supply chain can be generated by supplier failure or demand fluctuations, where the state of the system is measured by supply chain output or profit (Lee 2004). Standard prescriptions on how to incorporate resilience within supply chains address different levels of the system. These range from firm-level perspectives that favour flexible product designs, to systemic views that advocate that the entire chain of firms should become more flexible both vertically and horizontally, and strategic approaches, where suppliers are contracted to keep safety stock for customers, and multi-sourcing of products becomes common practice.

But precisely what is the relationship between resilience and the structure of a given supply chain? This question should be placed in the broader context of the rapidly growing field of network science, which has examined the topological robustness of complex networks across a range of domains such as food webs and networks of computer servers. To date it has been difficult to apply such interdisciplinary methods due to the absence of large-scale empirical data on supply chains, reflecting commercial sensitivities and the considerable difficulty of integrating multiple data sources consistently to map the complete set of interactions between companies. One key contribution of this paper is to provide precisely such a detailed map of a major supply chain, so that supply chain topology can be explored systematically.

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A number of reasons motivate our choice of focusing on the Toyota supplier network. As well as being able to cope with significant demand fluctuations, Toyota has demonstrated its resilience through its response to a major fire and a serious earthquake. As the company originated the notion of just-in-time production, the way it handled rapid material flows across its chain of producers was of prime interest to companies who wanted to join in the lean production bandwagon (for a recent review on the Toyota Production System please refer to the 2007 special issue of International Journal of Production on: “Celebrating the enigma: the continuing puzzle of the Toyota Production System”). Although most literature on Toyota is focused on its production system within the factory, the efficient flow of goods across the production chain demands considerable attention. As inventory is kept to a minimum with JIT, the flow of materials in and out of the factory should be smooth and well-coordinated to prevent any hold ups in production, given that there are minimal buffers to keep production going until problems are addressed. Toyota has not only been successfully in operating its JIT policy in a complex environment involving thousands of firms around the world, but it has also been able to rapidly reform and recover after a few well-documented disasters such as the Aisin fire and the Niigataken Chuetsu-oki earthquake, both of which caused Tier 1 supply disruptions (Nishiguchi 1998).

Exactly why and how Toyota is resilient is debated. Since Toyota only demands visibility up to the second tier, the overall structure of the supply chain must be considered emergent, rather than designed, although Toyota appears to be omnipresent along its supply chain (Nishiguchi 1998). Table 1 provides an overview of the research literature on the Toyota supply chain, which is largely based on extensive surveys and interviews with Toyota and its core supply base. Many researchers have examined the supply chain from the perspective of the quality of relationships between firms, and explored whether a culture rooted in trust and knowledge-sharing is what makes Toyota’s system resilient. Dyer emphasised the facilitation of knowledge management through associations (Dyer and Nabeoka 2000). Long-term relationships (Cusumano and Takeishi 1991) and the consequent building trust (Sako 1996) may lead to a cooperative culture and joint design processes. Trust is not only evident vertically between Toyota and its first tier, but also horizontally between suppliers in the same tier as shown by the common practice of outsourcing and the sharing of excess inventory. This is remarkable since Toyota encourages competition among its suppliers by making performance ratings public.

Knowledge sharing communities are seen as another possible answer to the performance of the supply chain, where supplier knowledge is within reach through a multitude of social inter-firm pathways (Dyer et al 1996). (Nishiguchi 2007) and (Wang 2008) hypothesised the Toyota network to have a *small-world* property, where the existence of many lateral ties enable suppliers to know each others’ capabilities and form cooperative strategies, helpful upon disruptions. Although network properties such as being “small-world” or having “community structures” are qualitatively hinted by these authors, sufficient empirical basis and analytical proof are lacking. According to Okuto, the network consists of more than 10,000 suppliers (also referred to as “nodes” in network terms), yet it is relatively smaller compared to its Western counterparts (Okuto 2003). Researchers observed that top assemblers have few connections, and suppliers mimic this structure downstream, leading to what has been described as *alpine* (Fujimoto and Takeishi 1994) or *fractal* structures (Seiji Manabe 2001), allowing firms to “specialise” in their relationships and sustain them in the long-term, giving rise to the development of know-how and trust.

Table 1 Overview of Studies on the topology of the Toyota Supply Chain

		Reference
Nodes	only a limited number of parts makers, making competitors visible to one another more than 10000 firms most of the essential suppliers are located in Aichi prefecture for optimal logistics	Fujimoto 2001 Fujimoto&Takeishi 1994 Nishiguchi 2007
	relatively small number of firms	Mari Sako 1996
Connections	high rates of spinning off parts development and manufacture to independently managed suppliers (as opposed to vertically integrating them)	Cusumano and Takeishi 1991 Mari Sako 1996
	long term relationships based on trust	Mari Sako 1996 Nishiguchi 2007
	multiple suppliers and multiple clients	Nishiguchi 1993

	most suppliers supply to a few customers evenly, as opposed to US suppliers that heavily depend on one primary customer	Nishiguchi 2007
	highly interconnected, strong-ties among most suppliers eliminating structural holes	Dyer and Nobeoka 2000
Communities	*small-world*, as opposed to regular US networks	Nishiguchi 2007
	segmented as arms-length and partner suppliers Kyoho-kai contains members from the Toyota group, 40 local shareholders, and medium sized enterprises, providing a forum for the exchange of know-how	Dyer, Cho, Chu 1996
	Part of a large "keiretsu", a family of affiliated companies allowing Toyota to remain flexible, yet enjoying merits of vertical integration without actual integration.	Dyer 1996
Structure	*Fractal* structure, where every supplier has similar numbers of connections	Nishigushi & Beaudet 2000
	Pyramid structure with many affiliated suppliers that each have their own suppliers, creating a group integration	Cusumano and Takeishi 1991
	Hierarchical structure but more "Alpine", with multiple top assemblers, rather than a "Pyramid"	Fujimoto and Takeishi , 1994
	(complex) network structure	Dyer and Nobeoka 2000, Sako 1996
	Hierarchical and multilateral	Fujimoto 1995 (J) Fujimoto 1997 (J)

Despite the many theories on the topology of the Toyota network, it is hard to understand whether and to what extent they contribute to its function. As a starting point it is important to explore the topological frame in which these cooperative, trusted relations are embedded can contribute to system-wide resilience. Beyond this structural perspective, it is then necessary to identify the role of other factors, such as multi-sourcing and diversified product portfolios. Despite a rich body of literature on the importance of supply chain resilience and Toyota's success, there is a surprising absence of systematic investigations into how the structure of relationships between firms may generate resilience, and how the resilience of the overall system and the topology of the supply network may be linked. In this paper we seek to address this significant gap in the literature, by presenting a large-scale empirical analysis of the Toyota supply chain that extracts those topological characteristics that we believe relate to resilience. Therefore, the main contribution of this paper is to unpack the notion of resilience in supply chains empirically and from the perspective of network theory.

We shall do so by two main modes of structural analysis. The first analysis is on robustness. We extract the robustness properties of the network by investigating to what extent it withstands the failures of its nodes compared to other possible topological realisations of the same network. In addition, we examine interdependencies among suppliers, which manifest themselves in the form of triadic enclosures. Then we examine structural characteristics that make Toyota robust to market uncertainty, such as product diversification. In the secondary analysis, we extract structural measures that relate to cooperation and degree of separation, with the notion that cooperation helps a supply network recover from failures, while a low degree of separation helps information sharing within the network.

In section 2 we review key studies of supply chain resilience, and ground our work in network theory. In section 3 we present the design of our research methodology. In section 4 we present our analysis. In section 5 we discuss the implications of our findings for theory and practice, and conclude the paper.

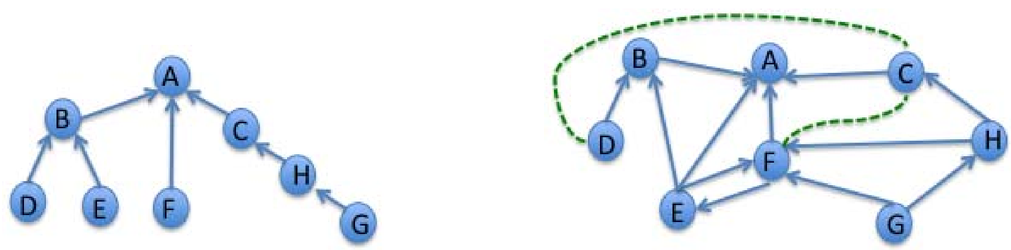
2 Theoretical Background

It is important to differentiate between resilience to demand fluctuations and to supply chain disruptions. Although the two are related, the secondary case results in a more extreme and possibly longer-term disruption in capacity. Another important consideration is the expectation from a resilient chain. One might call a supply chain resilient if its output is not impacted by disruptions or sudden changes, or a resilient chain can be one that retains the financial strength of those involved in it. In what follows we explore literature in supply chain shape, risk management and give a brief overview of relevant literature in network theory.

The simplest abstraction of a supply chain views the process of production in terms of the movement of materials along a sequence, or chain, of interconnected firms. However, as products and production processes have grown in complexity, necessitating tiers of suppliers, operations managers began to construct a hierarchical topology for supply chains, where each tier was connected to multiple suppliers. One consequence of globalisation has been that many top tier assemblers might be sharing their first tier suppliers, and that many suppliers not only have multiple suppliers themselves, but also multiple clients, which may overlap. Given the popularity of outsourcing strategies researchers started to focus on whether there were any inter-tier links where excess capacity was shared.

Going from simple sequential abstractions to the realisation that the shape of a supply chain might in fact be more complex, researchers started to investigate the types of links that may exist in them in the 1990s (Figure 1). (Gulati, Nohria and Zaheer 2000) argued that analysis of the strategic networks in which firms are situated is an important exercise for understanding firm strategy and performance. Lateral relations where a supplier's customer supplies to another supplier, cross-industry ties, and circular ties have been hinted by various authors (Lamming et al 2000, De toni and Nassimbeni 1995, Pfohl and Buse 2000, Harald). (Stuart et al., 1998) classified sequential ties as those that link assemblers to suppliers, and reciprocal ties as those among suppliers.

While several other authors pointed out the need to focus on the entire network rather than dyadic supplier to supplier relations for operational and tactical planning (Easton & Axelsonn 1992, Olsen & Ellram 1997, Zaheer and Zaheer 1997), Choi et al has been the one of the first to view supply chain management from a complex network perspective and has argued that the fundamental unit of supply chain relations should be the *triad*, where suppliers form relations among each other (Choi et al 2001, Choi et al 2009). In his "*net-chains*" analysis Lazzarini pointed out that conventional SCM focused on sequential dependencies, whereas in actual effect supply "net-chains" may exhibit reciprocal dependencies.



(a) (b)

Figure 1 (a) A hierarchical supply chain (b) A complex supply network with lateral relations. Supplier F is central to the production as it is involved in the highest number of links. E and F are involved in a reciprocal relationship. Suppliers D and C, and F and C do not have any direct relation but they share process know-how and technical knowledge.

Due to the lack of sufficiently large and comprehensive data sets, it has not been possible to empirically validate or generalise these observations, and consequently proposals advocating a systemic or networks perspective have not generated corresponding empirically grounded research. In his review of supply chain management practices New points out that "*diagrams of actual supply chains are almost entirely absent from literature*." (New, 2004)

The lack of a systemic view of supply chains does not only limit research, but is also evident within industrial practice. (Choi 2001) posits that even large organisations with well-developed supply chain management practices do not have visibility over their own supply chains. Supply chain mapping is a new industrial exercise, which came to practice after companies discovered the hidden costs of not knowing enough about the environment in which one operates through costly disruptions in the network.

Supply chain risk management literature have largely been unresponsive to the pleas of the authors above. Risk is there and growing though. The latest issue of MIT SLOAN Management review poses risk as one of the six forces that will be driving supply chain research in this decade (MIT SLOAN Man Review Winter 2010). Supply chain risk can be categorised into two main types (Snyder 2006): demand uncertainty and sudden failures of supply chain partners; be it longer term failures due to catastrophic events such as fires, natural disasters or terrorism, or shorter term failures such as machine stoppage. Strategies to counteract risk typically involve keeping safety stock and modularise product designs at the *product strategy level*, better forecasting and scheduling at the *plant strategy level*, and incorporating vertical and horizontal flexibility and dual sourcing at the *supply chain strategy* level (Table 2). While supply chain based strategies provide one with holistic solutions to risk, targeting those strategies is difficult, as one needs to have global information to pinpoint vulnerabilities. As a result, risk mitigation in industrial practice is largely confined to sophisticated but localised strategies.

Table 2 Strategies for Supply Chain Resilience

		Description	Demand fluctuation	Supply Disruptions
Product level	**Safety inventory** Parlar and Berkin 1991 Snyder 2005 Gupta 1992, 1996 Mohebbi 2004 Lee 2004	Determine how much safety inventory to keep at what stage, given demand uncertainty	Y	Y
	Product modularisation (Tomlin and Wang)	Keep product design standard, and flexible until later stages in the production process to account for variations in demand	Y	N
Plant level	**Safety Scheduling** Voudouris 1996 Daniels and Kouvelis 1995	Compute production schedules that maximize system flexibility	Y	Y
	Reliability prediction Tomlin and Snyder 2006	Forecast reliability of suppliers to plan for uncertainties in advance	N	Y
Supply chain level	**Location allocation** Weaver and Church 1985	Assign customers to production / distribution locations based on uncertain demand and supply	Y	Y
	Process flexibility Jordan and Graves 1995 Graves and Tomlin 2003	Model and improve manufacturing process flexibility within a single supply chain level	Y	Y
	Dual sourcing Tomlin 2006	Source products from multiple suppliers	Y	Y
	Vertical flexibility Hopp et al 2010	Determine optimal positions for process and logistics flexibility as a function of maximum expected profit in a multiechelon supply chain	Y	Y

Surely knowing the dependencies of one's suppliers matter when planning and coordinating one's own? Pinpointing vulnerable hubs can help mitigate risks and target strategies rather than attempting to find and fight the mysterious risk monster, which might come out of any dark corner. If significant suppliers are known, strategic plans can be drawn to keep stocks of high-risk inventory, find multiple providers, and modify dependant product designs so that changes can be adopted easily.

While strategies to deal with uncertainties provide us with valuable tools, drawing an accurate and concise picture of supply networks, could give us a very important glimpse of how an ecosystem of suppliers interplay, which in turn can have tremendous impact on our understanding of resilience.

Network science has a lot to offer in this respect. The past decade has seen an explosion of studies on how specific network shapes impact the resilience of it. We have seen reports on how a hub structure means that a network is resilient to random failures but vulnerable to failures on hubs, and how a randomly formed structure means random failures are disastrous for it. We have also seen how the formation of tightly connected groups with links among the groups leads to a small-world, where everyone is within reach of everyone else though a few degrees of separation, and how certain network characteristics change the speed with which information is diffused or failure propagates. It is worthwhile to briefly introduce the reader to classical complex network types and their significance, before examining which topology Toyota's supply chain has.

Social scientists were among the first to study complex networks, were primarily interested in acquaintance networks, where nodes represent people and links represent the acquaintances among them. Stanley Milgram famously declared the "six degrees of separation" theory that in the US, a person's social network has an average acquaintance path length of six (Milgram 1964). Many scientists later found that the theory held true in many large real-world networks, which, despite their large size, have relatively short paths between any two nodes.

Early network modeling efforts started with random models with no obvious pattern or structure, where each node had the same probability to link to another node. *Random networks* are statistically homogeneous because most nodes have a degree (the total number of in and out connections of the node) close to the network's average degree, and significantly small and large node degrees are exponentially rare. However, topologies of many real world networks are found to be more complex and unpredictable. Two measures quantifying network topology found to differ significantly in real networks are the degree distribution (the fraction of nodes with a certain degree) and the clustering coefficient. To explain the regularity of many networks found in real life, Watts and Strogatz introduced the concept of *small-world* networks, where starting from a regular, grid-like structure they re-connected nodes randomly, without allowing multiple links or loops (Watts and Strogatz 1998). This network class displays a high clustering coefficient (a measure that shows the extent to which triadic connections form in a network). Barabási and Albert then introduced *scale-free networks*, where nodes choose to form links to other nodes with a probability that is proportional to the number of links the node to be connected has (Barabási and Albert 2000). The reason they are called scale-free is because they lack a characteristic degree and have a broad tail of degree distribution. Numerical and analytical studies of complex networks indicate that a network's structure plays a major role in its response to node removal. Scale-free networks are more resilient than random or small-world networks with respect to random node loss. Large scale-free networks will tolerate the loss of many nodes yet maintain communication between those nodes remaining. However, they're sensitive to removal of the most-connected nodes, breaking down into isolated clusters after losing just a small percentage of these nodes. Random networks are vulnerable to random failures. *Exponentially scaled networks*, on the other hand, are similar to scale-free networks in that high degree nodes tend to have more links, but there is a finite threshold to the degree of nodes, which is shown by an exponential decay. *Hierarchical networks* are another relevant network type as they are thought to form the shape of supply chains, in which nodes are arranged as the branches of a tree. In pure hierarchies, branches on of the same level cannot connect to one another, and each node has the same number of links, except the root and base nodes. (Dodds and Watts 2003) introduced the concept of "ultrarobustness", which characterised networks with both connectivity and congestion robustness. They examined this concept in organisational information exchange networks. They found that introducing a relatively small number of random shortcuts to such networks resulted in ultrarobustness.

Three related empirical studies on supply chains consisted of (Choi et al 2001)'s efforts on mapping part of the Honda, Acura, Daimler Chrysler, which consisted of 70 members, (Lomi and Pattison 2006)'s analysis on 106 automotive firms in southern Italy, and (Keqiang et al 2008)'s examination of the Guangzhou automotive industry, consisting 84 firms. Both Choi and Lomi stressed that suppliers are likely to have multiple intra and inter tier relations, as well as different types of links, such as equity transfers and production links. Keqiang suggested that the supply network was "scale-free", meaning that suppliers attached to other suppliers with a probability based on its number of links, resulting in a hub-based structure. This observation however, is not verifiable as conclusions on such properties of a network are dependant on large sample sizes.

Due to lack of data, there has also been a number of computational network modeling efforts, starting with (Gafiychuk 2000')s hierarchically distributed supply network model where he observed the emergence of a scale-free network. Similarly, (Thadakamalla 2002,) and later on (Zhoa 2009) constructed models where scale-free supply networks emerged. While these models allow us to test vulnerabilities under certain topological assumptions, they are difficult to verify without real-world examples, and are largely based on the hierarchical abstraction that we have been envisaging for years.

3 Research methodology

As described in the previous sections, while there has been many studies on resilience in supply chains, there is a paucity of empirical research concerning resilience from a topological perspective and that which does exist raises the question of complex network effects, namely that it appears many types of lateral dependencies may exist in a supply chain, but its extent and impact is unknown. Furthermore, topological properties of supply chains may help explain how substructures and product diversification manifest at the system level and whether they bear any correlations to the resilience of a supply chain. Studies to address these questions have been largely absent from literature due to the difficulty in mapping large-scale supply chains. To address these issues the current study seeks to explore empirically the phenomenon of topological resilience in supply chains.

The reasons behind selecting the Toyota supply network as our empirical base are threefold: 1) the Toyota network has been one on which many resilience related theories and studies exist, which we may utilise for cross analysis, 2) given the scale of the Toyota motor company, the corresponding data is sufficiently large to derive statistical analysis, 3) the JIT emphasis on the Toyota supply chain also makes it more vulnerable to disruptions than push based manufacturers, which might manifest in the emergent supply chain shape.

The data used in the study is drawn from a selection of databases, which together contain financial, line of products and clients information for automotive firms. The first database (Marklines Automotive Information Platform[1]) uses data populated through surveys sent to about 40,000 automotive supplier firms and is primarily used by member firms to search for suppliers. The data is cumulative, in that once a supplier has identified itself as a supplier to a certain firm, it will remain so, unless either the client firm or the supplier firm requests a removal of the relationship. Therefore the data is not aggregated by a time-series, and might show relationships that are not continuous, although most data has been collected post 2006. The second database is Capital IQ[2], from which we gathered secondary data such as size of firms.

Data were downloaded from the databases during August - October 2010. The initial search involved identifying all companies that have a direct sales link to the Toyota Motor Company. This search resulted in Toyota's Tier 1 suppliers. This then was followed by individual searches on each Tier 1 supplier, identifying each company's suppliers, and other clients. This process was continued recursively until the third tier. Our construction thus includes three tiers, 3267 firms, of which 2196 are suppliers, and the remainder are other top tier clients. We have deliberately decided to include other top tier assemblers in our analysis as it is view that some of our resilience measures (such as lateral motifs) should include dependencies posed by the whole market. Thus, we differentiate analysis conducted using only suppliers and the whole network throughout the paper. It has to be noted that the firms within the dataset define themselves as automotive manufacturers. While their clients might or might not be members of the automotive industry, the data set is primarily automotive focused, and therefore is not exhaustive. (Nishiguchi 2007)'s estimated that more than 10,000 firms are involved in the manufacturing of Toyota automobiles. Thus our dataset, while largest sampled so far, is still a small subset of these firms, although data coverage until tier 3 is adequate as our numbers for Tiers 1-3 matches to that of (Nishiguchi 2007).

Another issue in the data sample construction involved methods of treating subsidiaries of a larger parent firm. We decided not to aggregate data from subsidiaries as these local subsidiaries are often independent and allow us to investigate geographic effects in the network. Another advantage is that we can see with increased granularity which subsidiaries produce which products, allowing us to draw more accurate resilience measures. All data were collected in a local database allowing the grouping of sets of firms based on various attributes including size, location, product lists, clients, and suppliers.

Following data collection, common metrics used in network science, such as degree distribution, path length, clustering coefficient, motif analysis have been used to explore the shape of the network and relations to resilience revealed; as well as, properties specific to supply chains have been investigated by deriving resilience measures relating to product diversity, and multiple instances of product types in the network.

4 Topological Analysis on Resilience

Table 3 shows a breakdown of the supplier firms within the dataset by country of incorporation and size. Not surprisingly, the majority of the supply chain remains in Toyota's mainland Japan. However, there is a well-developed spread across several other countries with the majority being in Europe, and Asia. One might wonder whether this spread is intentional to increase the options of Toyota, in case domestic suppliers run into trouble. Of course an alternative explanation might be that overseas companies offer unique products that Japanese suppliers do not, or that they offer products at a cheaper price, and hence their existence within the supply chain does not have anything to do with resilience. A more detailed study of the product mixture behind the firms in overseas countries will be necessary to establish whether either one of the hypotheses might be valid. Another observation is that the majority of companies

[1] www.marklines.com
[2] www.capitaliq.com

within the supply chain are small to medium enterprises. While the vast majority of Tier 2 suppliers have less than 500 employees, Tier 1 suppliers show a relatively broader distribution.

Table 3 Firms by size and country of incorporation

Number of employees	Percentage of suppliers	Tier 1	Tier 2	Country of incorporation	Percentage of suppliers	Tier 1	Tier 2
<100	36	27	59	Japan	64	60	66
100-500	40	33	33	Other Asia	16	16	17
500-1000	11	14	4	Europe	15	18	11
1,000-10,000	12	23	4	North America	4	5	5
10,000-50,000	1	3	0	South America	1	1	1
50,000-100,000	0	0	0	Australia	0	0	0
>100,000	0	0	0	Africa	0.1	0	0

4.1 An exponential network

Exploring tier membership, multi-tier suppliers form the majority of Toyota's suppliers: as we queried listed customers of the second tier, we found that %76 of Toyota's second tier suppliers also supplied to other top tier assemblers such as Honda, Mitsubishi, Nissan, Daimler Chrysler and so on. A significant number of suppliers were also shared with related industries including firms like Motorola, Lockheed Martin or Sony. Single tier suppliers consisted of 26% of the network, with purely hierarchical path lengths of two or more consisting of only 4% of the network. This finding signifies a low average path length, meaning that Toyota places itself a 2.06 degrees of separation from its second and third tier suppliers in our dataset, where the degree of separation is defined as the number of nodes, i.e. suppliers, Toyota must traverse before reaching to a particular supplier through a sales link, signifying that Toyota's third tier is within reach through one supplier typically, which might be significant with regards to the social context Toyota embeds itself, allowing the fast diffusion of know-how and reputation within the network.

Figure 3 shows the incredibly multifaceted structure of the supply chain, where the long-envisaged hierarchical tiers are replaced with a complex network structure. Suppliers have an average degree of separation of 3.37 from any other node within the network. This low path length makes one think of a tightly knit community where a Japanese SME is only 3 companies away from an Austrian SME supplier of other giants such as BMW. This might be true but does that link imply unknown lateral dependencies i.e. if a supplier in Austria moves its wings, can there be a hurricane in Japan? To analyse this, we will have to investigate what are known as clustering coefficients and dependency motifs later on.

Shifting our focus temporarily back to the overall structure, we find that the average number of clients per supplier is 1.96 while the average number of suppliers is 2.22, both quite small numbers. However averages have a way of hiding significant variations and the actual degree distribution might tell us something more. Figure 3 shows the supplier degree distribution of the chain. The degree distribution contains only those supplier firms that have declared their supplier and clients.

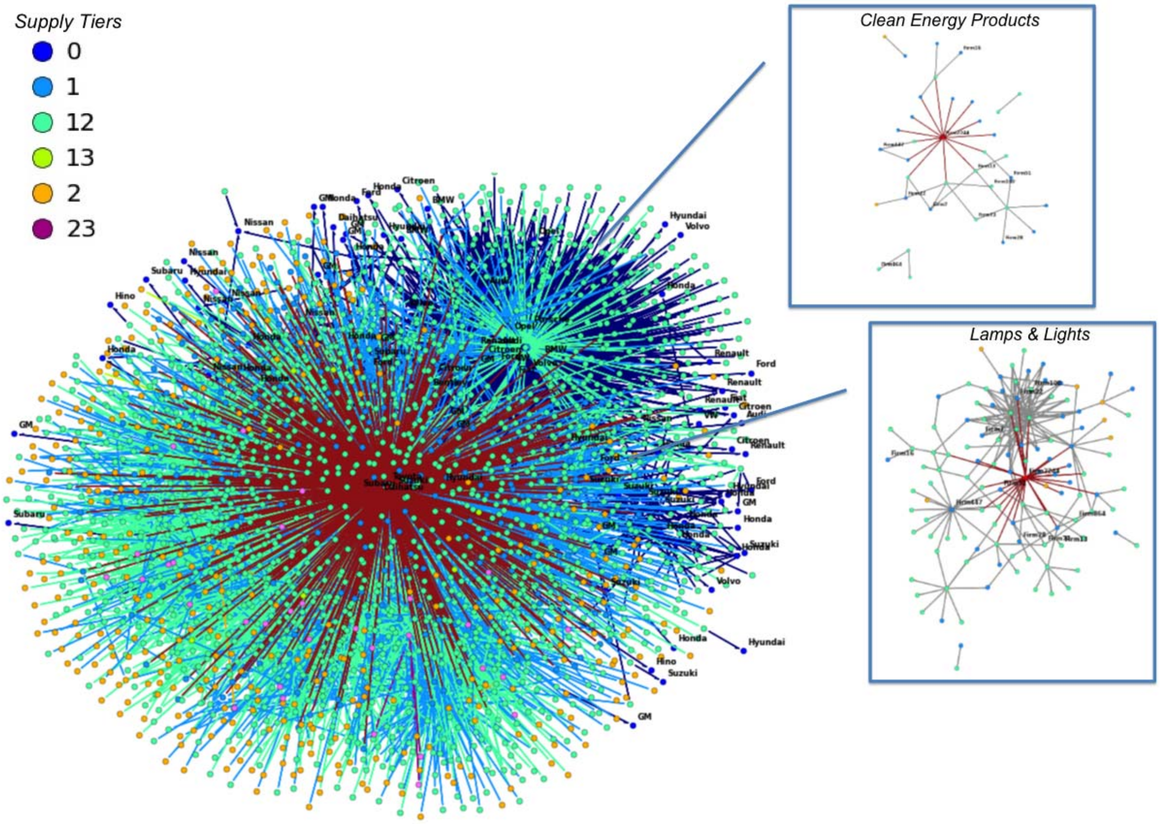


Figure 2 Toyota's complex supply network: Light blue nodes are pure Tier1 suppliers. Toyota is at the centre of the universe with its links in red. Single and multi-tier suppliers are colour coded according to the tiers they belong. Dark blue nodes are a set of well-known automotive assemblers. The visualisation algorithm clusters firms that have more common links together, which is evidenced by Japanese suppliers forming one cluster at the centre, and European firms another one at the north east. Different product groups have different topologies. A denser topology with multiple hubs is evident in the lamp suppliers, while a more uniform link distribution is evident with clean energy products.

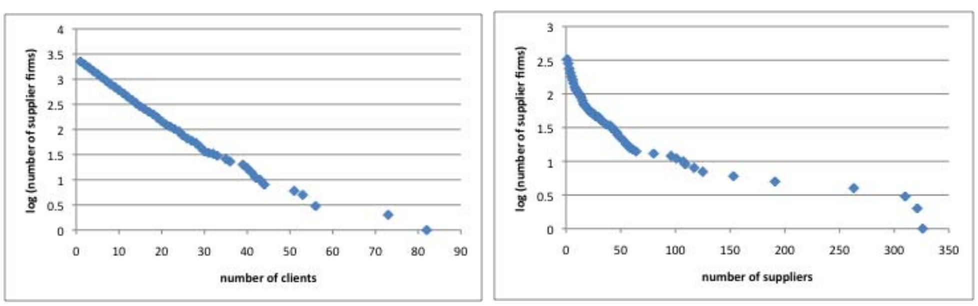


Figure 3 Supply chain degree distribution (cumulative)

We see that the network does not scale linearly, but has an exponential curve defining the limit to which it can scale, i.e. limiting the number of suppliers to firms. This is a different observation than those of Thadakamalla et al and Zhoa et al, who suggested supply chains to be scale-free and heterogeneous, largely shaped by a *preferential attachment law* that describes nodes favouring highly connected nodes in their linking preference. The hypothesis was based largely on reputation, where the number of links a supplier has serves as a proxy for its reliability. Given the exponential curvature, it is not difficult to imagine instances where the hypothesis might not necessarily hold true in a supply chain, where supplier selection can be much more complex than a simple popularity index. Although popularity of a supplier might serve as a measure of its credentials, it is by no means the only criterion. For example aerospace giant Boeing selects its suppliers with no less than 32 criteria, including reliability, pricing, and location. Governmental mandates on preferences being given to minority owned or SME firms might be other criteria that are factored into selection. In addition, high numbers of clients might not necessarily be a positive factor for a firm who wants to gain competitive advantage by dominating a supplier. Therefore we would expect a more variable linkage pattern in supply chains, which is evident in the dataset.

What does this degree distribution mean in terms of robustness? While there is a limit to the largest connected hub size, we see that there are a few large hubs, making the network vulnerable to failures on them, simply due to the fact that more numbers of firms will be impacted when these hubs fail. It might be that most of these links carry products that are multi-sourced, but disruption, however slight, is still likely until alternatives are found and sourced. On the other hand, random disruptions are more likely to impact smaller nodes, as there is a larger portion of them, making the network resilient to random disruptions. To find out, we subjected the network to a procedure called *percolation*, in which one removes supplier nodes and observes when the network forms into disconnected clusters.

Although this classical percolation procedure gives network scientists a general idea of vulnerabilities based on the network shape, it is obvious that a supply chain essentially functions with an inherent dependency tree based on production bills of materials and therefore a more complete failure analysis would need to include such dependencies. Our first intuition is to examine product redundancy, a measure that defines how much a product type is multi-sourced.

The dataset contains 833 generic product types, and the corresponding dependency tree. We can derive the product redundancy measure in the network as :

$P_r = \frac{\sum_{i=0}^{l} d_i}{m}, \forall d_i > 0$ where *d* is the number of times product type *i* occurs in the network) *l* is the number of different product types, *m* is the number of suppliers.

We find that the average product redundancy within the whole network is a remarkable 5.28 with 5.55 in Tier 1 and 4.57 in Tier 2. Only 9% of all products are not multi-sourced and 3% of the suppliers carry unique products, 10% of which belong to the Japanese supplier association Kyoho-kai (for a detailed discussion on the Kyoho-kai please see Section 4.2). Of course, we are working with product types rather than exact products and bills of materials, hence the number is artificially higher than what it would be in the case of a particular production route containing 30 to 40 thousand parts (Cusumano and Takeishi found that the average supplier number per part was 1.3 in 1991 in Japanese auto-manufacturers). However, the product type information still manages to give us an idea of the higher level capabilities of each firm within the dataset, which can serve as a proxy for what firms might potentially be substituted.

Based on the product dependency information the percolation process is carried out as follows:

1. A supplier node is removed randomly and the degrees of all associated product types are reduced by one,
2. Any nodes, which had the node deleted in Step 1 as their only customer or their only supplier, are deleted, going back to Step 1,
3. If any product type in the product dependency tree is lost as a result, the procedure terminates. Otherwise we go back to step 1.

To investigate the impact of failures on highly-connected hubs, we repeated the same procedure, where instead of random suppliers, we targeted suppliers with links higher than the average number of links in the network. The percolation procedure above resulted that an average of 6.22 random, or 3.78 targeted consequent failures are needed for the production to malfunction (Table 4). On the other hand, disruptions at any unique producer such as Aisin, will result in the malfunctioning of production almost immediately, as inventory is kept minimal. Given the low correlation between the number of links a supplier has and the size of its product portfolio (0.48), one wonders if targeting highly connected nodes for testing robustness is indeed the right test. An alternative test could thus involve examining the failure of nodes with products that are rare in the network, meaning that suppliers that have a high “product market share” *M*, than average are targeted. In other words, Instead of removing nodes randomly as described in Step (1) of the percolation process above, we remove node j with a probability proportional its product market share, defined as:

$M_j = \sum_i^n \frac{1}{p_i}$, where p_i is the number of instances of product type *i* offered by supplier *j* in the network, and n is the total number of product types offered by supplier *j*.

the rest of the process remains the same. The rather fast break-down of the network with this type of targeted failure shows that indeed it is a supplier's "product market share" that really matters when it comes to robustness as opposed to the number of links a supplier has (Table 5).

But is it this particular mixture of the exponential structure and product mix on nodes that results in a high percolation threshold, or would any other network structure give the same result? To find out, we have generated two "null models" to compare with the Toyota network. In the *first null model* Toyota's the degree distribution is preserved, and product mixtures on nodes are randomly shuffled across the suppliers. This gives us essentially the same structure as the Toyota network, but with uniformly and randomly distributed products rather than having some suppliers with more numbers of products. In the *second null model*, we generated a randomly connected network, where every node has on average 4 links, and the product mixture is kept the same as the original network. We repeated the percolation process on each of the 10,000 such randomly generated null models, and averaged across to find percolation thresholds. Table 4 displays our results.

Table 4 Percolation thresholds in the Toyota network and null network models[3]

	Toyota supply chain	Null model 1	Null model 2
Random percolation threshold	6.22	5.51	5.23
Degree targeted percolation threshold	3.78	5.42	3.79
Market share targeted percolation threshold	3.19	3.79	3.01
Average path length	3.37		5.04
Clustering coefficient	0.22		0.03

So it seems there is indeed something special about both the network structure and the product mixture projected on that structure that makes a supply network robust against failures. We can trace back the first ingredient to network theory. Due to exponential topology the network is robust when random suppliers fail, but not so when highly connected ones do. In the randomly connected null model we have similar vulnerability to Toyota's network in degree-targeted failure, which is puzzling. Let us examine then the second ingredient. What is special about the product mixture?

It is interesting that our first null model displays higher robustness to targeted supply disruption than the Toyota network, particularly when we target suppliers with high product market share. In some ways this is expected – in our null model we have a uniformly distributed product portfolio that is randomly shuffled, which means we do not have "product hubs" that make the network functionality vulnerable. Random failures are unlikely to impact product hubs in Toyota, but they will impact a randomly shuffled model more as there are no hubs. As degree product portfolio size and degree size has low correlation, random and degree targeted failure do not have much difference. Of course the null model is unrealistic, as one cannot simply redesign its supply chain by randomly shuffling production, but it gives us an idea of what product portfolio distribution might make a supply network more robust. It is also understandable that in real life suppliers will have an incentive to make themselves indispensable by producing rare products. What the null model shows, though, is that this local incentive inevitably results in bottom-up supply disruption vulnerability if failure occurs in "production hubs".

A related theory is that of (Choi 2001) on robustness, where he argues that suppliers close to end-consumers need to have a more diversified product portfolio to obtain resilience to demand uncertainty. Given this hypothesis we would expect the number of product types being offered at Tier 1 suppliers to have the highest degree distribution, followed by Tier 2 and Tier 3 suppliers. Figure 4 verifies our expectation.

The keyword in Choi's hypothesis is demand uncertainty, which is a top-down disruption, as opposed to bottom-up supply network disruption. The former requests that upper tier suppliers become product hubs, producing a multitude of products to hedge. The latter requests that they

[3] Since Null Model 1 and the Toyota network has the same structure but different product distributions, the average path length and clustering coefficients are the same.

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share their duties uniformly, and offer similar numbers of products and product market share.

It seems that Toyota's network demands different product portfolio structures for it to cope with demand uncertainty and supply disruptions. Given that these two types of robustness demand different structures, it might be that the first need is more critical and structure has emerged accordingly. However, it is safe to say that Toyota's network is still robust to bottom-up disruption, compared to manufacturers that are still incorporating dual-sourcing to their supply chain. At first the high level of multi-sourcing appears to contrast the long-term supplier relationship strategy Toyota typically pursues, and one consequently wonders if multi-sourcing is indeed a strategy Toyota has generated for robustness, as it continues to enjoy long term, stable relationships with a subset of these suppliers.

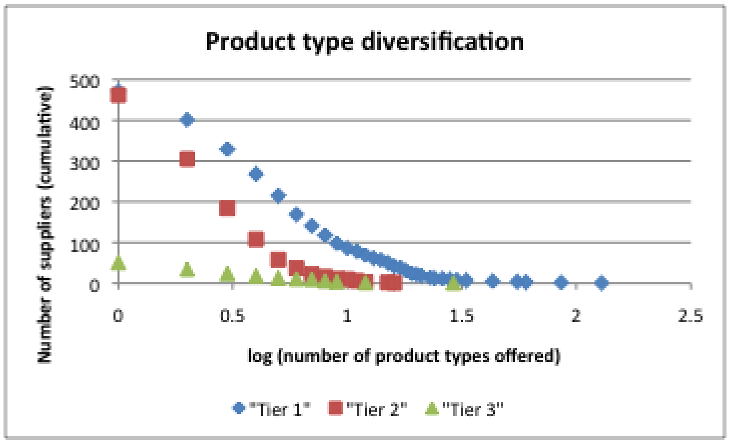


Figure 4 Product diversification by Tier

So far we have seen the impact of the general topology of the Toyota supply chain. If we zoomed-in, we would see that this particular topology implies links among same tier members, and among firms bypassing several tiers leading to complicated dependency patterns, or as the network scientists call "*motifs*". In terms of triadic patterns, we might expect to see cyclic or lateral enclosures, where the former would refer to a firm's client supplying to the same firm's supplier, and the latter would refer to two suppliers supplying to the same client, and also supplying to one another. When we searched the whole network for such patterns, we found that lateral motifs consisted of 24% of all Tier 1 suppliers' total relationships, and 14% of Tier 2 suppliers' total relationships (Figure 5). Cyclic patterns were not found in any Tier. Referring to Choi et al 2009's analysis it appears lateral triads indeed might be a significant part of automotive supply networks.

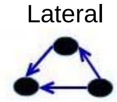
	Cyclic 	Lateral 
% of Tier1:	0	0.24
% of Tier2:	0	0.14

Figure 5 % triadic enclosures within the network

Under the assumption that products flowing on these links are used for producing dependant assemblies, this implies there are significantly high numbers of dependencies acting on the network.

However, when we examine dependencies within geographical locations, we see that most of them are contained within Japan, with European countries and North America following next, albeit with much smaller portions. Repeating our percolation analysis to suppliers from certain countries we found that an average of random 5.3 Japanese, 7.1 European, or 6.1 North American suppliers need to fail to for the Toyota network to fail (once again, these numbers shall be taken as suggestive of a trend rather than being definitive). This analysis hints that most unique production is contained within Japan. For further analysis we have run a community detection algorithm in the whole network based on (Newman and Leicht 2007)'s method. The method works by clustering groups of companies that have high number of relationships together. The analysis showed that of the 11 sub-communities found, 7 of them were formed by

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relationships among suppliers from the same geographical region, meaning geography influences density of relationships to a significant degree. Hence, going back to our question in Section 4.1, it seems that the Austrian supplier's wings generate a slight breeze rather than a hurricane in Japan, and actually what matters most for Toyota are Japanese suppliers. One consequently wonders if overseas suppliers serve mostly to offer cheaper alternatives, shorten distance from overseas markets or indeed as buffers against possible disruptions within the network, which is unfortunately a question that can only be answered with transaction data.

Table 5 % lateral relationships among geographical locations

	Japan	Asia	EU	North America	South America
Japan	78%				
Asia	2.3%	0.16%			
EU	6.2%	0.21%	2.7%		
North America	4.7%	0.22%	14.7%	14.7%	
South America	0.36%	0	0	0	0

Nevertheless, this highly inter-linked nature can be considered a two-sided coin in terms of resilience. While the high percentage of lateral relations implies dependencies and vulnerability, such connections may also result in a "small-world" effect, where firms are not too far away from each other and may potentially utilize those relationships in the form of information sharing, know-how exchange or outsourcing. Of course, the existence of a small-world effect does not mean that it is actually put to full use, which we will investigate in Section 4.2. However its mere existence might hint that there is higher potential for cooperation than in a non small-world network if the number of links, particularly if neighbourhood links serve as a proxy for reputation.

We have already seen that the average degree of separation i.e. path length, is small, compared to null models. To conclude on the small-world effect we need another measure named the *clustering coefficient,* which computes the number of enclosed triadic relations within the network over the number of possible such enclosures. In other words, the local clustering coefficient of a node in a network quantifies how close its neighbours are to being a completely connected network. Thus the higher the coefficient is, the denser a network is, with many triangular relations. A network is said to have small-world properties, if its average clustering coefficient is significantly higher than its random null model, and if the network has approximately the same mean-shortest path length as its corresponding random null model. Formally the clustering coefficient of a local node is calculated as:

$C_i = \dfrac{k}{n(n-1)/2}$, where k is the number of triadic enclosures in which node i participates, and n is the number of links of supplier i

thus the average clustering coefficient becomes:

$C_{AV} = \dfrac{1}{N}\sum_{i}^{N} C_i$, where N is the total number of suppliers in the network.

As Table 4 shows, we find that the Toyota supply is indeed a small-world network, with a higher clustering coefficient and lower path length than its random counterpart.

4.2 A cooperative network?

Intuitively, another resilience factor to take into account is cooperation among suppliers. Although cooperation manifests itself in many ways, from joint design processes to exchange of technical know-how, a possible way of exploring cooperation within our dataset could be to investigate the ratio of suppliers that are involved in cooperative relationships over the number of suppliers who have the potential to do so, by using the product type information attached to each firm. Since all firms in the network are ultimately Toyota's suppliers, firms that produce same products are competitors. Having a client-supplier relationship with a competitor could then help us detect a cooperative drive in the network.

There could be two types of cooperative relationships, which we term as reciprocal and outsourcing relationships. Reciprocal relationships are those in which firms act as both client and supplier to one another. More formally, we calculate reciprocity R as:

$R = \frac{\sum_{s=0}^{m} \frac{l_r}{L_s}}{m}, 0 \le R \le 1$ where l_S is the number of reciprocal relationships of supplier *s*, L_S is the total number of relationships of supplier *s*, and *m* is the number of suppliers. This reciprocity coefficient in the network has been found to be 1.21e-7; quite a low figure compared to what we would expect from a random network with the same number of nodes and connections (0.0027 with null model 2).

Next we investigate outsourcing, where two firms produce the same product type, and have a client-supplier relationship. Formally put, we measure:

$O = \sum_{p}^{P} \frac{2l_p}{n_p(n_p - 1)}, 0 \le O \le 1$, where l_p is the number of existing links between suppliers who produce Product type p, n_p is the total number of suppliers of Product type p, and P is the total number of product types repeated within the network. The outsourcing coefficient is found to be 0.0075, considerably higher than reciprocity, but still a similar figure to what we would expect from a random network model (0.0025 with null model 2).

Related literature, however, tells us that Toyota does have a cooperative culture, at least among its core suppliers. The Aisin fire case showed that cooperation among core suppliers was a key factor in its recovery (Nishiguchi 1998). Since our dataset contains non-temporal relations, one can argue that the low figures above might simply be due to our inclusion of non-important, one-off suppliers. If we focused only on core suppliers would we see that they have higher dependencies? Would there be more outsourcing among them? Each of these questions can potentially tell us something about cooperation and resilience. Since we do not have temporal data, a good way to isolate core suppliers from the rest could be using data on association membership.

Kyoho-kai is the oldest and most famous supplier association in Japan, as it happens, it is the association that contains Toyota's suppliers. Kyoho-kai was formed during the second world war as automotive suppliers united to channel funds and materials which only Toyota could secure as a result of the rationing. After serving its initial purpose, the association shifted its focus to the exchange of technical know-how. It currently has 211members, and reportedly forms 98% of Toyota's total purchasing on parts (Sako 2009).

Benefits on membership to supplier associations form a debate in literature. As Mari Sako pointed out recently, the three distinct views of Kyoho-kai members are that a) membership is valuable in that it provides a stable relationship to Toyota, reducing marketing costs, and allows the supplier to grow in technical capability, both of which in the long run exceeds the disadvantage of having to offer lower unit prices Toyota, b) hypothesis (a) was true in the past, and as suppliers have gained technical know-how, and started to diversify risk by trading with several assemblers in 1980s, thus the associations are nothing more than social clubs, c) associations form an ideal basis for exclusion of other suppliers, particularly foreign suppliers and serve to monopolise profit.

Through extensive surveys with several Japanese supplier association members and non-members, Sako found that membership to associations increased in number over the years, but on average pre-tax profitability was lower in members than non-members, refuting the third theory. Those firms that complied with the second perspective were declining in profit, and those that were of the first view experienced growth. If the first view is actually what drives suppliers to join in the Kyoho-kai, we would expect this cooperative drive to manifest itself in terms of higher levels of cooperative activities. It is also important to note that Toyota owns 10% or more of the shares of 41 of these companies, which more likely than not may serve as an incentive for cooperation.

We found that the outsourcing coefficient is significantly higher within the Kyoho-kai association, at 0.21, meaning that Kyoho-kai suppliers who are involved in producing similar types of products do have higher levels of sales links among each other compared with the rest of the network. Furthermore, Kyoho-kai suppliers seem to have much higher numbers of links among them, at an average of 19.74 compared to the network average of 4.14. While we do not know whether it is association membership that causes access to higher links and openness to collaboration, or vice versa, we can safely state that the core supply network of Toyota is indeed a more cooperative and tightly knit one (Figure 6).

Another important finding is that out of 72 unique product type suppliers, 15 belong to Kyoho-kai, so this makes %1.5 of non-Kyoho-kai suppliers carry unique product types, but about 7% of Kyoho –kai members carry unique product types. Once more one cannot be certain of the direction of causality, as we cannot conclude whether it is high product market share that puts

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pressure on suppliers to join the Kyoho-kai or Kyoho-kai members naturally offer more unique products because they are specialized for Toyota. We might however speculate that such unique product producers are rightly cocooned within tight connections as the exchange of knowledge involved in producing these unique products might prove valuable if production needs to shift, as happened in the Aisin fire case.

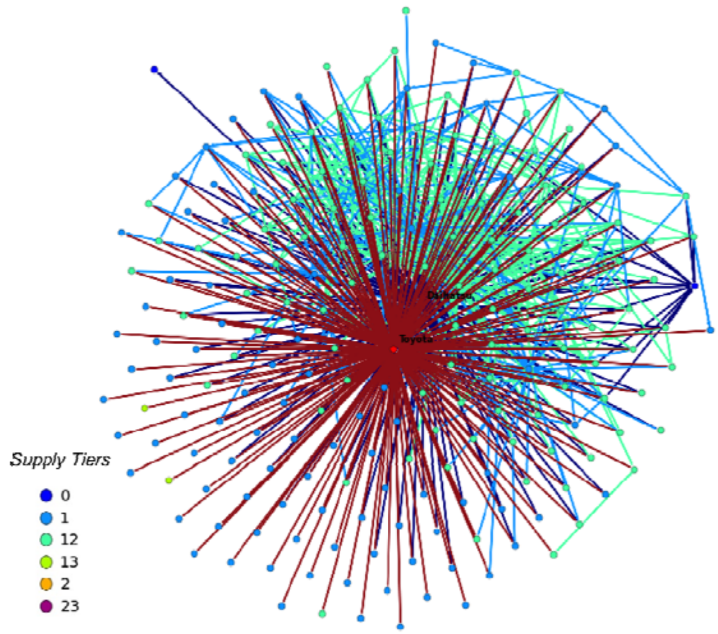

Figure 6 Kyoho-kai supplier association: Tier0 assemblers are shown in blue (including Toyota, Daihatsu and Subaru)

5 Theoretical and practical implications

Looking back to literature describing Toyota's supply chain, we can see that the observations of many authors hold valid through the lens of this set of empirical data. For example, high number of horizontal ties suggested by literature is apparent by firms participating in multiple tiers. The Alpine and complex network structure is evident through the existence of multiple clients and suppliers per firm. The significance of Japanese based suppliers is apparent from the high density of connections among Japanese firms. The small-world structure is evidenced by low path lengths and high clustering in the network.

So what can we learn from this analysis? First is that there is a high chance that some large supply chains are complex networks and do not match with the simple hierarchical structures we have envisaged for years. 23% of the Toyota network consists of triadic interdependencies, which is too significant a figure to be neglected. Latest research points us in the same direction, with authors such as (Choi 2009, Borgatti and Li 2009) urging supply chain researchers to investigate triadic relations, and reciprocal dependencies. Of course this does not mean models of flow, risk and uncertainty relating to simple hierarchical structures are redundant, but it means that they need to be extended to consider multiplicative and cascading effects resulting from embodiment in a complex network. Establishing a complex network view on supply chains present us with three challenges: (i) challenges of shifting mindsets, (ii) challenges of data collection, and (iii) challenges of modeling.

The first set of challenges may result from shear frustration towards the complexity of a global supply chain, and a lack of understanding in why complexity matters. Firms need to know their network environment and focus on triadic relations for three broad reasons:

- Dependencies might mean synergies in improvement. If a particular supplier is highly central to the network, improvements in that supplier may help a multitude of other suppliers and thus create higher returns.
- Dependencies can also mean cascading failures. If a firm runs out of stock, all dependant clients at the upper tiers will do so, gradually failing as dominoes. Determining the centrality of suppliers within the network can help pinpoint vulnerabilities. During the production of B787s Boeing realized that a subset of their Tier 1 suppliers were also supplying to other Tier 1 firms. They feared that failure in any of these firms would disrupt operations significantly and concentrated their effort on multi-sourcing parts from suppliers in lateral relationships.
- Dependencies impact the planning and coordination strategies pursued in supply chains with the introduction of feedback loops.

Manufacturers need to accept that seemingly random changes in a supply chain are not truly random, but in fact are the result of complexity, and effort needs to be devoted in understanding the governing patterns in the system (Choi et al 2001). Planning each dyadic relationship independently with a random fluctuation can bring more harm than harmony.

The second challenge for firms here is the collection of large-scale data to understand a dynamically changing supply chain. Using archival data, or data from independent companies or monitoring organizations could present firms with some options. Of course, data collection can be simplified by distinguishing between primary and supporting suppliers (Lambert and Cooper 2000), and starting from key products. Commercial sensitivities need to be assured. Top assemblers are central to data collection due to their bargaining power in accessing information. The arrival of supporting traceability technology such as the *Internet of Things* might make future supply chain mapping much easier. Once collected, modeling and simulation studies may be the next step carried out to investigate impact of changes in topology.

The third set of challenges is the lack of supply chain network models that consider improvements and cascading failures. Operations research and management has a long-standing tradition of focusing on linear, dyadic ties. New models need to be explored to incorporate multi-tier membership, and understand governing rules and patterns in large-scale systems.

The second insight we can gain from this study is related to topology and resilience. As we found with Toyota, an exponentially scaled network first means that there is a limit to which it can grow. The growth limit on the network might imply cognitive constraints on firms in dealing with multiple links or cost that occurs in sustaining links. The topological consequence is that the network has high resilience to random failures but is vulnerable to failure in its most connected hubs. However this generic topological implication needs some thought before being applicable to supply networks. Indeed what we see is that when it comes to failure analysis both the supply chain topology and the multi-sourced product mixture projected on that topology matter. Interestingly one cannot collapse the two properties into one, as the number of connections of a supplier is not highly correlated with its product portfolio size.

Interesting questions also rise about types of resilience and what they mean in terms of topology. Resilience against demand uncertainty posits that product diversification should manifest at the upper tiers more than the lower tiers, such that changing needs of assemblers can be accommodated quickly and changing demand from different assemblers can be hedged against. On the other hand resilience against supply disruption demands uniform product distribution across the network, eliminating “product hubs”. It seems that the two demands are in conflict to some extent at the upper tier level. The former topological implication holds true in the Toyota network, which might be an evolution due to the higher frequency of the former risk.

The third consideration resulting from this work is that the high number of dependencies and inter-tier connections can be a two-sided coin, as such topology implies vulnerability but also potential cooperation. As we have seen with Toyota, the network is much more dense at its cooperative core, with the average number of connections increasing from 4.14 to 19.74, and 21% of suppliers producing the same product types having sales relations.

It could be that Toyota’s supply chain topology have evolved in a way that supports Toyota’s production and supply strategies (Table 6). For instance, *heijunka*, or *production leveling* is a Toyota specific strategy, used to minimize variation in operations, sometimes even at the expense of lost sales to due price adjustments to control demand. To implement heijunka, the supply chain support that Toyota needs is predictable lead times from supply partners, the boundaries of which can only be established through specialized production processes, requiring time and trust to develop. The topological support that we observe for heijunka might indeed come from triadic motifs, where incentives to specialize are high as the supplier is embedded in a whole community that is working with Toyota. The dense structure results in what is known as a small-world network, where firms have a low degree of separation from one another. This might have many implications. One might even speculate that the small-world structure allows suppliers to obtain reputation information, fostering trust and facilitating those long-term relations and know-how exchange on which Toyota strives. Multi-sourcing might be another factor that supports heijunka, as Toyota could substitute another supplier if one fails to deliver, and keep operations smooth. We also know that Toyota spins off more parts to be engineered at suppliers than western automotive suppliers, and demands zero-defects, which can only be achieved through the fostering of the supply base in terms of production process knowledge. A common lean philosophy needs to be built, which might be evident in the increased number of connections in firms that belong to Kyoho-kai. For the supply chain system to support just-in-time production, firms should be in geographical proximity, so that small lot sizes can be shipped frequently and cost-effectively. This is also evident through the geographically based communities we see in the network topology.

Table 6 Toyota SCM strategies and topological support

Toyota SCM strategies	Needs	Topological support
Lean logistics/SCM	Zero defects Long-term relations Consignment inventory Common geography to support JIT production JIT suppliers	A core, dense sub-network that facilitates the Kyoho-kai Geographical communities
Heijunka	Long-term relations to develop expertise and experience for least variation Trust to foster specialization in product development Incentives to specialize in product development	High interdependency Most firms have small numbers of suppliers and clients allowing focused relationships Small world structure allows reputation information to be defused and fosters trust Multi-sourcing of products allow hedging to reduce supply variability
Exchange of know-how	Incentives to share knowledge Trust Facilitation of exchange	High interdependency A core, dense sub-network that facilitates Kyoho-kai Small world structure allows reputation information to be defused and fosters trust
Outsourcing	Long-term relationships to generate technological know-how Multi-sourcing for risk avoidance	Unique production is mostly within Kyoho-kai that supports know-how exchange Most product types have multiple providers

We envisage two main avenues of further research. Our first need is to gain a deeper understanding of complex supply chains and its implications. Questions to be explored include whether topology is a result of firm strategy, i.e. how supply chains of other automotive manufacturers differ from Toyota structurally. Comparative studies and performance data in this respect would be very valuable as it could help us understand correlations between client size and performance, or product portfolio and performance given the network effect. In terms of resilience, there is a need to understand how the combination of individual attributes investigated here such as path length, outsourcing, clustering coefficient, product portfolios, and multi-sourcing impact resilience. Future research, which explores the extent to which these attributes explain robustness and resilience will be valuable.

Finally, our study has a number of limitations, including the lack of non-temporal and transaction data, which in turn provide opportunities for future research into the evolution of complex supply networks. Temporal data could not only help distinguish between the core network and the support network, but also help us understand patterns of growth and shrinkage in supply chains, and observe how supply networks behave when subjected to certain environmental parameters. Transaction data can help us infer the nature and significance of relationships. For instance, given historical data on supply chain disruptions, and how transactions on the network shift, one can quantitatively deduce the extent to which cooperation plays a role in the recovery of the network by examining goods or information exchange between the firm that had the disruption and its competitors.

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